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d [illegible] substances specifically for the use of their own plants, much of the development of materials is done by a central organization—Materials Engineering—which serves the whole company. The variety and scope of problems tackled by this department are tremendous. This is occasioned by the innumerable materials of all kinds used by the electrical industry, and by the innumerable different ways it uses them.

First of all, Materials Engineering maintains and operates a full complement of physical and chemical testing laboratories, in which it tests most of the thousands of kinds of materials used by the company. In this manner it provides technical assistance and serves as a consulting organization to the Purchasing Department, to design engineers, and to the operating divisions that use the materials. But the major activity of the department is in the development and application of new materials. This phase of its activity is far from being strictly a laboratory procedure. The basic idea often originates in the Research Laboratories; then Materials Engineering takes over. Laboratory investigations are made, manufacturing techniques are studied, methods of fabrication planned, standard procedures worked out, and, finally—in many cases—a pilot-plant operation established. The products of this pilot manufacture are sold to operating divisions, and in some cases to outside manufacturers, before the process is finally transferred to the appropriate division.

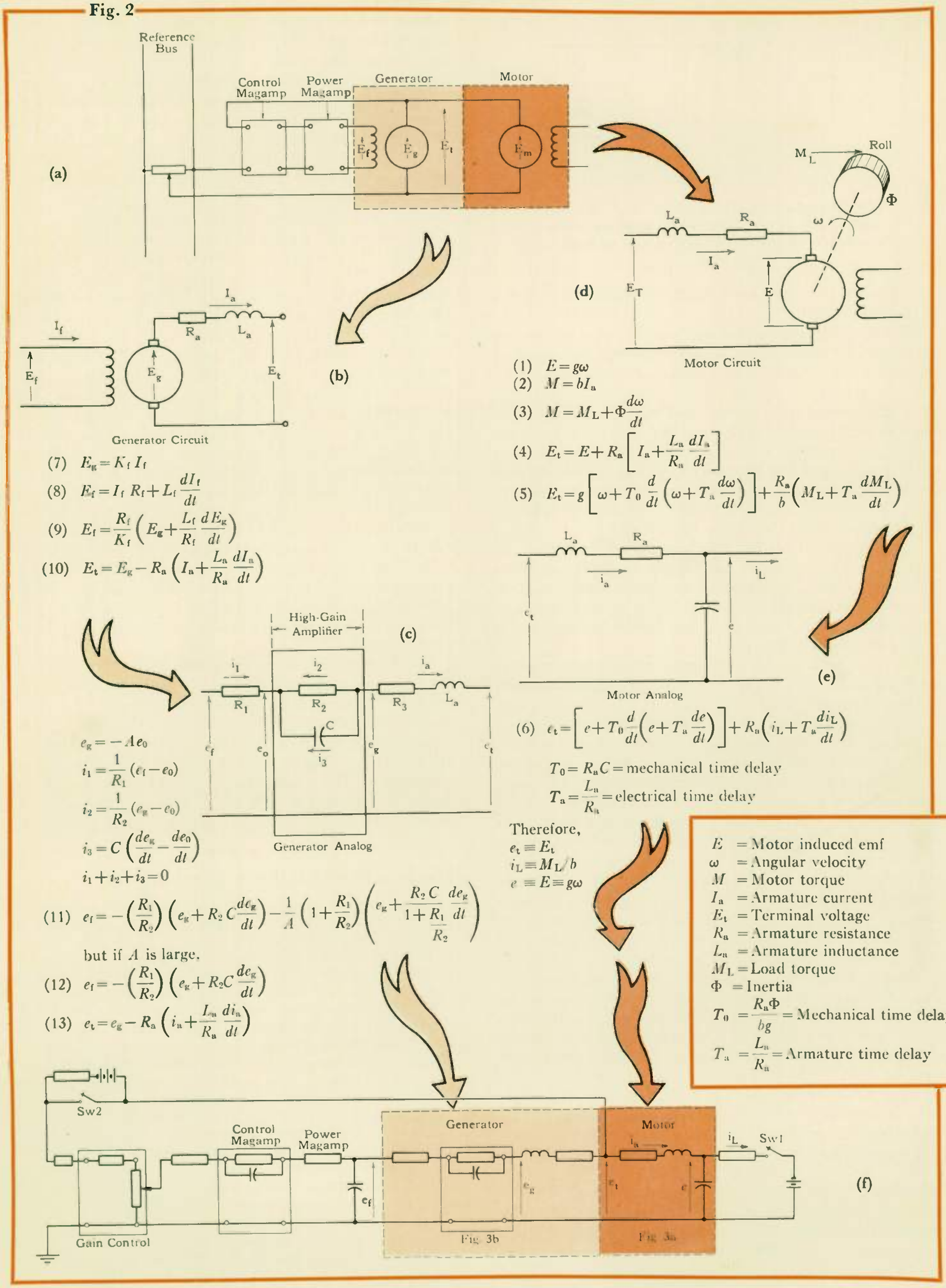
Many materials have been either born or developed in the Materials Engineering laboratory and production facilities. Discaloy, a high-temperature alloy used for many turbine parts, was developed here after basic work was done in the Research Laboratories. Like many other alloys, its manufacture was a critical process involving exacting procedures. Materials engineers fought the problem through, developed methods of manufacture and fabrication. Westinghouse still produces some ingots, but has turned over the fabrication to outside suppliers, who use Materials Engineering methods.

A few years ago a young chemist in the Research Laboratories discovered a new foaming resin, subsequently named Insulfoam. This resin—the lightest solid known to man—showed promise as a thermal insulating material. The job of exploring its potentialities was handed to the Materials Engineering Department, which has subsequently found several practical uses for the resin, and is still considering many possibilities.

In 1946 the need for a very small, compact, sensitive, but sturdy device was apparent for certain military applications. This would need the characteristics of an electron tube, but have greater reliability. At this point the magnetic amplifier had attracted considerable attention in this country. Finding the best materials appeared to be an obstacle, so materials engineers tackled the problem of supplying such a small sensitive device. They quickly discovered that some of their previous developments—namely Hipernik and a potting resin—had already solved some of the problems. A major obstacle yet remaining was the need for a selenium rectifier that was more sensitive and temperature stable than any then in existence—by several times. Eventually engineers came up with an improved process of making selenium rectifiers. But this was as yet a laboratory procedure. Next came the problem of quantity manufacture to rigid standards. This, too, was solved, with the end result that materials engineers established a pilot plant to manufacture both rectifiers and magnetic amplifiers. This pilot operation has now reached the stage where it is able to produce a commercial Magamp as well as the military version.

These are but random examples. Dozens of others could be cited were space available. These few hardly serve to illustrate the variety and scope of materials problems, but they do suggest the type of work conducted. The full list would be a staggering array—ranging in type from cost reductions and materials savings, to materials improvements and development. The list of substances worked with would be even more staggering. It would cover nearly all metals and most alloys, chemicals, impregnating resins, paints and varnishes, cloth, glass, casting materials, plating compounds, insulating materials (both thermal and electrical), petroleum products, and many others. The rapidly expanding and steadily changing scope of the electrical industry will certainly demand much in the way of new and improved materials. When it does, materials engineers will be ready to furnish the answers.

Fig. 2



(1) $E = g\omega$

(2) $M = bI_a$

(3) $M = M_L + \Phi \frac{d\omega}{dt}$

(4) $E_t = E + R_a \left[I_a + \frac{L_a}{R_a} \frac{dI_a}{dt} \right]$

(5) $E_t = g \left[\omega + T_0 \frac{d}{dt} \left(\omega + T_a \frac{d\omega}{dt} \right) \right] + \frac{R_a}{b} \left(M_L + T_a \frac{dM_L}{dt} \right)$

(7) $E_g = K_f I_f$

(8) $E_f = I_f R_f + L_f \frac{dI_f}{dt}$

(9) $E_f = \frac{R_f}{K_f} \left(E_g + \frac{L_f}{R_f} \frac{dE_g}{dt} \right)$

(10) $E_t = E_g - R_a \left(I_a + \frac{L_a}{R_a} \frac{dI_a}{dt} \right)$

(6) $e_t = \left[e + T_0 \frac{d}{dt} \left(e + T_a \frac{de}{dt} \right) \right] + R_a \left(i_L + T_a \frac{di_L}{dt} \right)$

$T_0 = R_a C$ = mechanical time delay

$T_a = \frac{L_a}{R_a}$ = electrical time delay

$e_g = -Ae_0$

$i_1 = \frac{1}{R_1}(e_f - e_0)$

$i_2 = \frac{1}{R_2}(e_g - e_0)$

$i_3 = C \left(\frac{de_g}{dt} - \frac{de_0}{dt} \right)$

$i_1 + i_2 + i_3 = 0$

(11) $e_f = -\left(\frac{R_1}{R_2} \right) \left(e_g + R_2 C \frac{de_g}{dt} \right) - \frac{1}{A} \left(1 + \frac{R_1}{R_2} \right) \left(e_g + \frac{R_2 C}{1 + \frac{R_1}{R_2}} \frac{de_g}{dt} \right)$

but if A is large,

(12) $e_f = -\left(\frac{R_1}{R_2} \right) \left(e_g + R_2 C \frac{de_g}{dt} \right)$

(13) $e_t = e_g - R_a \left(i_a + \frac{L_a}{R_a} \frac{di_a}{dt} \right)$

Therefore,
$e_t \equiv E_t$
$i_L \equiv M_L / b$
$e \equiv E \equiv g\omega$

E = Motor induced emf
ω = Angular velocity
M = Motor torque
I_a = Armature current
E_t = Terminal voltage
R_a = Armature resistance
L_a = Armature inductance
M_L = Load torque
Φ = Inertia
$T_0 = \frac{R_a \Phi}{bg}$ = Mechanical time delay
$T_a = \frac{L_a}{R_a}$ = Armature time delay

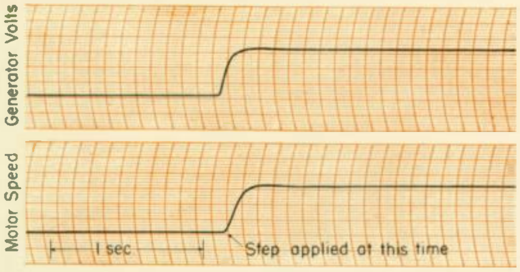


Fig. 3—Typical results obtained from Anacom studies. This is the response of a steel-mill drive to a suddenly applied change in voltage setting.

3. Interpretation of overall system performance in terms of the end product.

Prior to the development of the Anacom and other suitable computers, by far the most difficult phase was the second requirement—translation of component-part performance into overall system performance. To make the problem amenable to solution, simplifying assumptions were necessarily made (such as linearization of component characteristics) and some factors were assumed to be negligible simply because they could not be coped with by usual methods of calculation. As a result, the designer could determine fairly well the steady-state performance, but could predict only sketchily the dynamic performance of his regulating system.

The Anacom has reduced this heretofore difficult phase of analysis to a rather simple and rapidly executed procedure. Take, for example, the regulating system for a cold strip tandem mill. Assume that the general layout of the system and the analysis of component parts has been completed, and is given in the form of Fig. 2(a).

With the Anacom, all components and factors, whether electrical or mechanical, are reduced to simplified electrical analogs. Therefore the first step is to devise the electrical analog of the system. The procedure for doing this is shown in Fig. 2(b), (c), (d), (e). First the analog for the motor is devised. Several relationships can be immediately set up. Motor speed can be related to induced emf (equation 1); motor torque can be equated to a function of armature current (equation 2). Similarly, motor torque can be written in terms of load and acceleration (equation 3); and terminal voltage in terms of induced emf and armature current (equation 4).

Combining these several equations, a relationship between terminal voltage, motor speed, and load torque can be established in terms of the mechanical time delay and the armature time constant. In a computer operation such as this, electrical and mechanical quantities must be combined into one electrical analog. Thus in the motor, speed and voltage are equivalent, as are current and torque; inertia can be represented by a capacitor. Thus an electrical circuit analogous to the original motor can be established. Compare the equation for this analog with that derived for the motor. Note that they match, term by term (i.e., $e_t \equiv E_t$ $e \equiv g\omega$, $i_a \equiv I_a$, $i_L \equiv M_L/b$). Also we have terms for the mechanical time constant ($T_0 = R_a C$) and the armature time constant ($T_a = L_a/R_a$). Thus the analog is a suitable representation of the motor.

A similar procedure can be followed for the generator. Here a field voltage (E_f) produces an internal generator voltage (E_g). Load current through the armature resistance and inductance reduces this voltage to the terminal voltage (E_t). Several other relationships are apparent: Induced voltage is proportional to the field current (equation 7); the field voltage can be related to field current (equation 8); also the induced voltage can be expressed as a function of field current (equation 9); and finally, the effect of armature voltage drop is included in equation 10.

To represent a portion of the system gain, an amplifier is incorporated in the generator analog. The input and output voltages of the generator analog are given in equation 11. Because the amplifier gain (A) is very large (about 5000) the second term of the equation is unimportant and can be neglected (see equation 12). A comparison of the generator equations (equations 9 and 10) with the analog expressions (equations 12 and 13) shows that the analog is suitable.

To construct the analog for the entire regulator system the analogs of the various components are assembled, as shown in Fig. 2 (f). The relationship between the analog and the regulating system is the same as exists between the a-c network calculator and the system it represents, i.e., it is an easily reconstructed miniature of the system.

With this analog, different operating conditions can easily be simulated on the Anacom. For example, the effect of applying load can be obtained by closing a switch (Sw 1) on a high resistance in series with a large voltage. Opening another switch (Sw 2) simulates a sudden change of reference. The regulating system can be subjected to conditions of disturbance akin to those found in actual operating conditions, and the response of the regulator noted. The response of the tandem-mill drive system of Fig. 2 (a) to suddenly applied change in voltage setting is shown in Fig. 3. Similar reactions of the mill to changes in operating conditions are easily simulated.

To have value, the Anacom's results must be translated into quality of end product. This must be done by engineers intimately familiar with the application and manufacture of the product. Experience and common sense are the primary factors required.

The Anacom has played a vital role in the development of regulating systems by reducing the major obstacle in the analytical process. The ability of the computer to evaluate system performance rapidly and economically allows the designer more flexibility and an opportunity to try out systems and ideas too radical or novel to build on a full scale without confirmation. The Anacom has thus filled a vital need in the design of regulating systems and has played a major part in enabling the design of the fast, precise systems now in use.

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Electric Power Kit—A Teaching Aid

In this "age of miracles" children are apt to overlook or underestimate the importance of electric power to our industrial, economic, and social life. A new Electric Power Kit, designed by the Westinghouse School Service Department, is intended to aid teachers in instruction of this vital subject. It was developed with the guidance of many nationally known educators.

The kit consists of four basic related parts: (1) a set of three charts, which illustrate life in three ages—Muscle Power, Steam Power, and Electric Power; (2) a three-dimensional model of a modern electric-power station, which comes unassembled, but with complete instructions, so that the students can assemble it; (3) a student booklet containing, in sketch and cartoon form, important facts about electricity and electric power; and (4) a Teachers' Guide, to suggest ways in which the material can be used, and to provide a complete background for the teacher, including source references. The combined kit is intended primarily for use in social studies in elementary and junior high schools, but all, or parts of it, is suitable for various courses.

This Electric Power Kit is intended for distribution to schools through electric power companies. Further information can be obtained from School Service, Westinghouse Electric Corporation, 401 Liberty Ave., Pittsburgh (30), Pennsylvania.

Regulating Systems for the Steel Industry

The difficulties encountered in taming a lion don't hold a candle to the problem of controlling a strip of steel traveling at 7000 fpm in a rolling mill. Or that of reversing a heavy "bloom" from base speed in one direction to base speed in the opposite in a matter of a couple of seconds. Modern industrial regulating systems have solved these and many other knotty problems involved in high-speed processing of steel.

W. R. HARRIS, *Manager, Metal Working Section, Industry Engineering Dept., Westinghouse Electric Corporation, East Pittsburgh, Pa.*

AUTOMATIC regulating systems are a well-established and integral part of electric drives for the steel industry. The most pertinent reasons for this are the widespread and increasing use of continuous mills and processing lines, and the trend toward higher speeds, both of which make regulating equipment mandatory. An operator, no matter how expert, is not physically or mentally capable of performing the complex functions required to tie together continuous processes, or to control properly a high-speed drive during acceleration or deceleration.

The tandem cold-reduction mill is a classic example of increase in operating speeds, as shown in Fig. 1. The first tandem mill was installed in 1928. Its top rolling speed was 340 fpm and the total horsepower of the five motors driving the stands and the reel was 1020. By 1936 the speed of most mills was about 1500 fpm, more than a fourfold increase. Since that time the speed has risen at a phenomenal rate; one mill scheduled for operation soon has a maximum speed of 7000 fpm. The average speed of the 10 five-stand tandem cold-reduction tinplate mills installed since 1946 is 4696 fpm.

Many technical advances in drive equipment have been necessary to obtain operation at these speeds. Outstanding among these is the individual-generator system, which requires a regulating system that has exceptionally quick response and stability.

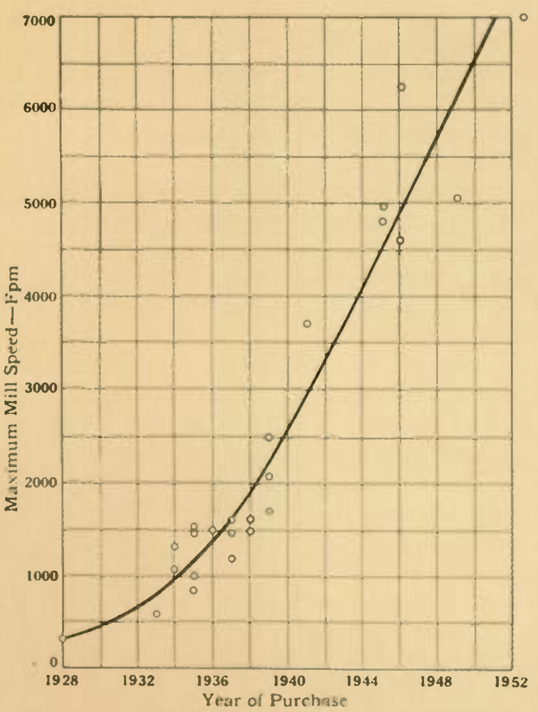


Fig. 1—This shows the steady rise in top speed of five-stand tandem cold-reduction tinplate mills.

The man-hours per ton of finished steel, shown in Fig. 2, is a remarkable reflection of the effect of continuous mills and higher processing speeds. The curve shows a rapid decrease in required man-hours for 1939 and 1940, which followed major developments in high-speed continuous rolling of hot and cold strip. The high tonnage capacity of such installations caused the shutdown of many old hand mills. The electrical-manufacturing industry shared in this development to an unusual degree; such mills would have been impossible without the development of successful drive systems. During the war years the man-hours per ton remained relatively constant as the industry concentrated on maximum production from existing facilities. Since then, increases in speed and in use of continuous mills have considerably lowered the man-hours per ton.

The tremendous capital investment of the steel industry in production facilities and high labor costs requires the use of all available means of increasing production and improving product uniformity. Thus the industry demands the best drive equipment and regulating systems; it has followed an aggressive pattern of technical developments and acceptance of any new or improved system that promised to pay its way.

The number of regulating systems used on the drive of a modern steel mill may surprise those not connected with the

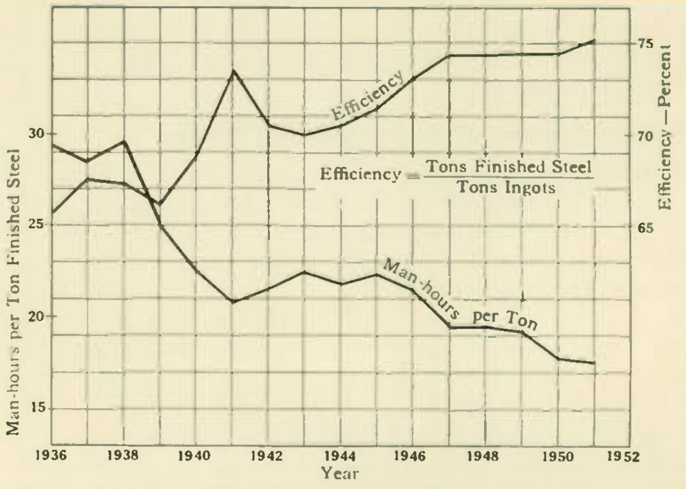


Fig. 2—Man-hours per ton of steel have gradually decreased and efficiency of operation has increased. The trend to higher speeds and continuous processes has been largely responsible.

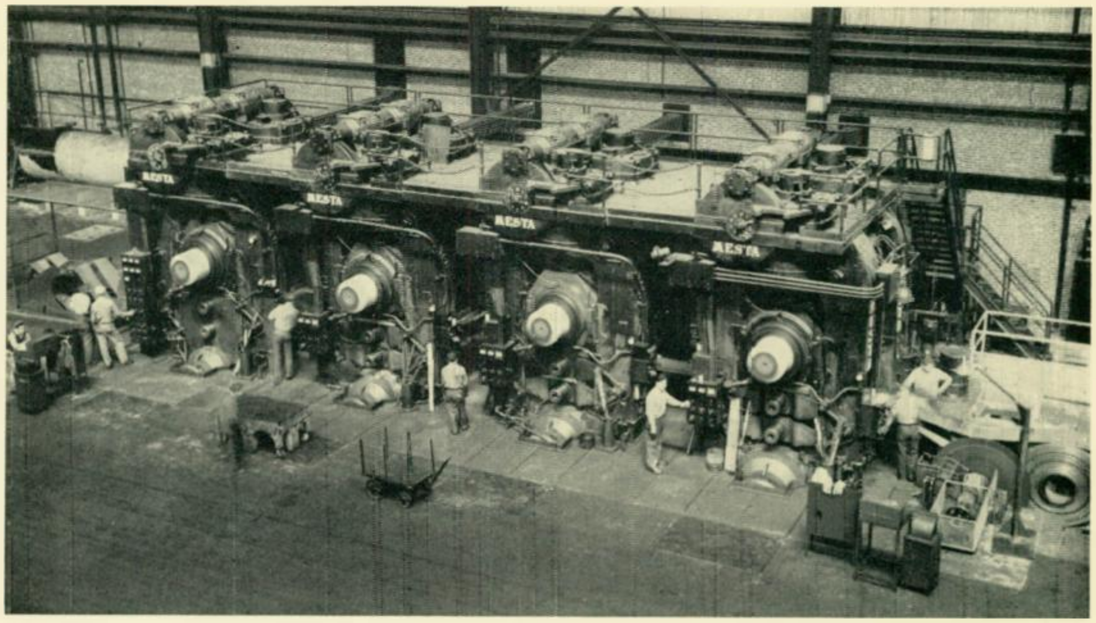


Fig. 3—A four-stand tandem cold-reduction mill that cold reduces steel strip from 0.1 to 0.01 inch thickness. Each stand is driven by a d-c motor; the small motors on top of the stands are used to "screwdown" against the rolls to provide roll pressure. The total horsepower applied to mill stands and reels in mills such as this varies from 10 000 to 20 000 for modern high-speed mills.

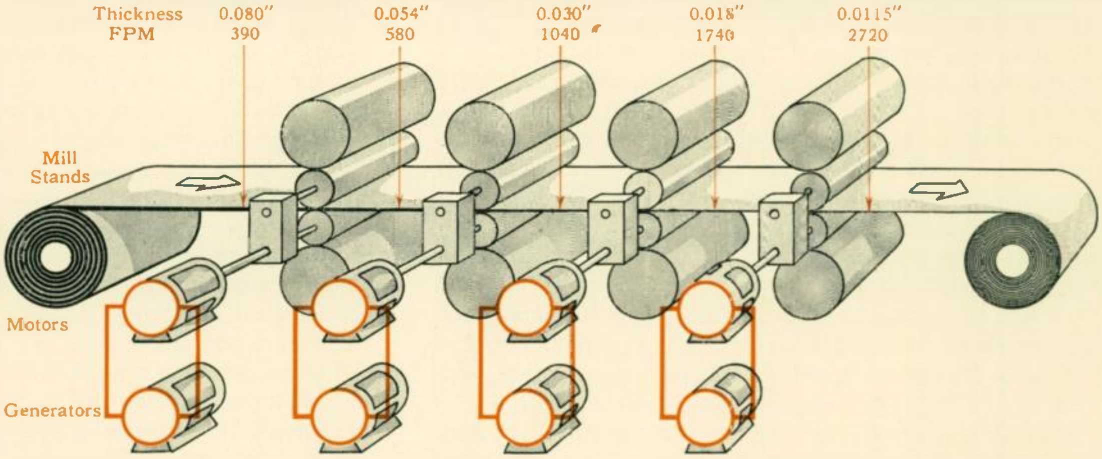


Fig. 4—Schematic arrangement of a tandem mill with individual generator drive, showing the thickness and speed of the strip between stands.

industry. For example, at the new Fairless Plant of the U. S. Steel Company, Westinghouse is supplying drives for a skin-pass mill, a cleaning line, the finishing stands of the hot-strip mill, and the main drive for the 40-inch blooming mill. The total horsepower of these main and variable-voltage auxiliary drives is 61 350. The control of this large horsepower requires 51 rotating regulators, three magnetic-amplifier regulators, three electromechanical regulators, and one electronic regulator, for a total of 58.

Requirements of Mill Regulating Systems

In selecting a regulating system for a steel-mill drive the primary considerations are (1) the steady-state accuracy required, (2) the transient response required, (3) the degree of stability necessary, and (4) a high degree of availability coupled with low maintenance.

The steady-state accuracy requirements for most steel-industry drives are moderate. Only a few, such as tandem cold-reduction mills and rod mills (where impact drop must be minimized) require very precise steady-state accuracy.

The steel industry requires an unusual degree of transient response and stability on drive regulating systems. This is true because even the so-called "continuous" mills—such as cold-reduction mills, skin pass and temper mills, and a variety of processing lines such as cleaning and side-trimming lines—must reduce speed or stop to allow a finished coil of steel to be removed from the mill and a "raw" coil substituted. These changes in speed upset the regulated function. Good transient response is necessary for a quick return to normal; good stability is necessary so that the regulating system does not add further disturbance.

Other mills—electrolytic tinning lines, continuous pickling lines, and continuous galvanizing lines—utilize a truly "continuous" process; however, in these mills one section of the line must be stopped—while the process section continues, sometimes at reduced speed—in order to weld or stitch on a new coil, or to eject the finished coil from the system and start the strip on a new reel.

Reversing mills, i.e., blooming, slabbing, or plate mills, also require fast transient response and good stability. Both the main drive and the auxiliary drives (such as tables, screwdowns, and manipulator fingers) must reverse rapidly to pass the steel back and forth through the rolls. After the metal passes through the main rolls, the auxiliary drives must position the screwdown quickly, reverse the tables to bring the metal back to the mill, and perform the manipulating operations required in preparation for the next pass.

Regulating systems for such drives must have quick transient response either to accomplish the operation in the desired time or to maintain a close tie between different parts of a system during changes in speed. Often exceptional stability is required to maintain the proper tension between units to prevent breaking the strip or "throwing" loops. Military applications are generally considered to have the most rigid criteria for regulating system stability. However, steel-mill requirements consistently exceed them.

The foregoing comments have stressed regulating systems rather than the regulators themselves. The regulator is merely one component of a total system. To obtain the most from these systems, good regulator design must be coupled with good basic motor and generator characteristics, and good control—all tailored to fit the application. The regulating element, no matter how excellent, cannot fully compensate for improper characteristics elsewhere in the system. For example, excess saturation in a generator can lower system amplification and impair system performance just as effectively as a poorly applied regulator.

Typical illustrations of regulator applications in the steel and allied metal-working industries are the individual-generator tandem cold-reduction mill drive, the main and auxiliary drives of a slabbing mill, and the drive for a high-speed side-trimming line.

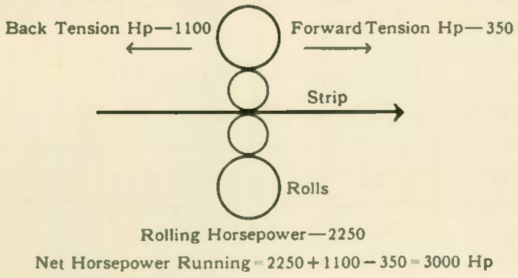
Tandem Cold-Reduction Mill Drives

Steel strip used for cans, refrigerators, stoves, automobiles, and toys is the product of cold-reduction mills, such as that shown in Fig. 3.

The metal must be threaded through the stands at relatively slow speed. The mill is then accelerated to operating speed and runs at this speed until the coil is nearly finished, when it is decelerated to slow speed to let the end of the coil go through the mill. Although the top operating speed of such mills has increased tremendously, the threading speed has not increased appreciably, and the resultant wider speed ranges have multiplied drive problems.

A four-stand tandem cold-reduction mill provided with a modern individual-generator drive is shown in Fig. 4. Strip thickness decreases as the metal travels through the mill. The speed of each successive stand increases accordingly. It is necessary to accelerate the complete mill and to maintain proper speed and tension relationships between the individually driven stands and the reel. The tension horsepower between stands is a considerable portion of the total motor load, and the accelerating torques can equal or exceed the rolling torques. For example, the fourth stand of a mill driven by a 3000-hp d-c motor has the following loads:

Rolling horsepower	2250
Back-tension horsepower	1100
Forward-tension horsepower	350
Net horsepower running	3000
Accelerating horsepower	2100
Net horsepower accelerating	5100



The drive problem is further complicated because, for reasons not well understood, during deceleration periods the thickness of the metal increases as much as 15 to 40 percent. The drive must be designed to fit this mill characteristic so that the gauge is maintained as closely as possible without exceeding safe tensions between stands.

With individual-generator drive the voltage of each stand generator is matched to a reference bus voltage through a precise control system that is in full control from standstill to maximum speed—an infinite range. Such a system has the highest requirements in the industry, as follows: (1) high steady-state accuracy to assure close tracking of all stands from threading to running speeds and to prevent creeping of the motors at standstill; (2) very fast and well-damped transient response to assure proper maintenance of tension between stands during acceleration, deceleration, and emergency stops, and to prevent "rocking" when stopping; (3) adjustments must be simple and independent of one another so the system can be quickly installed and tuned and so that maintenance is simplified; and (4) most important, the system must have a high degree of flexibility so that it can easily be set up to roll a wide range of schedules.

A schematic diagram of the drive and control system for one stand of a tandem cold mill is shown in Fig. 5. Each stand has a similar drive arrangement. All generator voltages are matched to the reference bus through a Magamp control system. The generator voltage is compared with the reference voltage and the difference applied to the control Magamp, which in turn controls the power Magamp and the generator field. To compensate for the resistance drop in the armature circuits of the stand motor an IR-compensation Magamp is used. This modifies the voltage relationship between the generator and the reference bus and increases the generator voltage in proportion to the current in the main circuit. Such compensation is used on all modern drives to improve acceleration characteristics so that the motor speed more nearly follows the generator voltage, to ensure that the metal

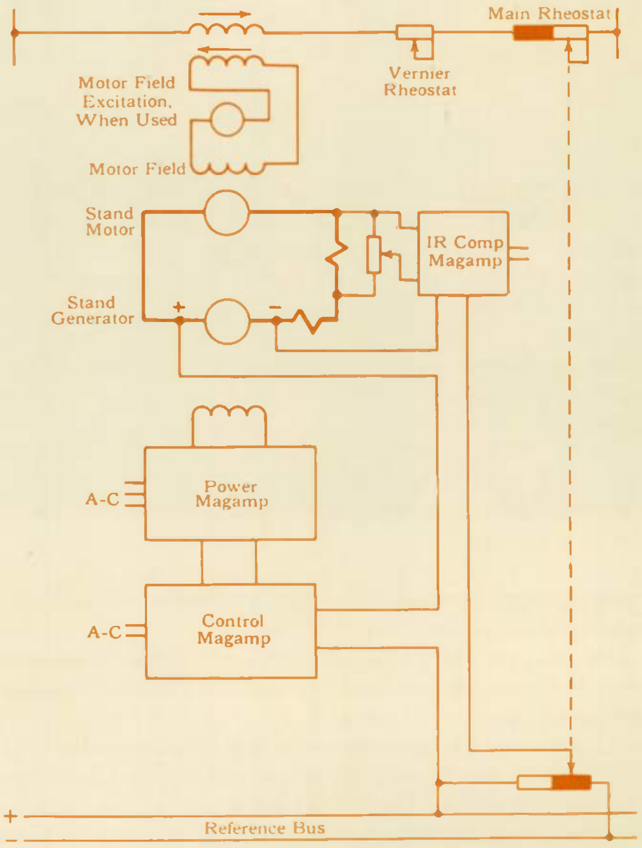


Fig. 5—Schematic diagram of Magamp magnetic-amplifier regulator for an individual-generator tandem cold-mill drive.

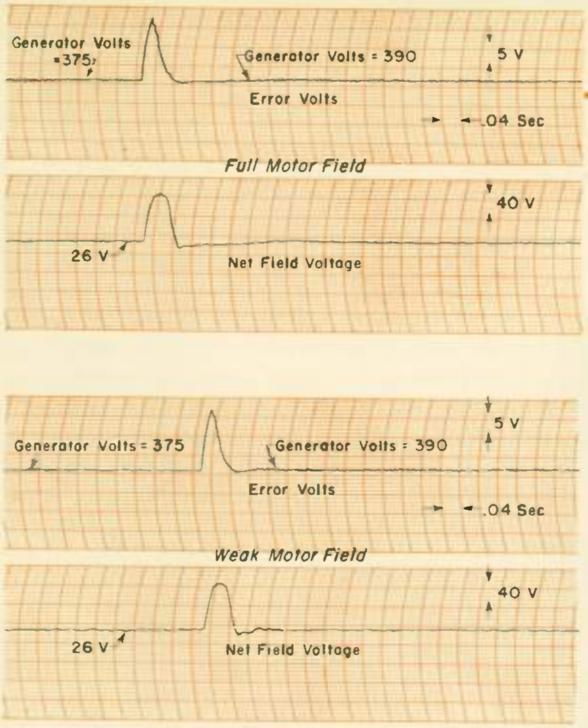
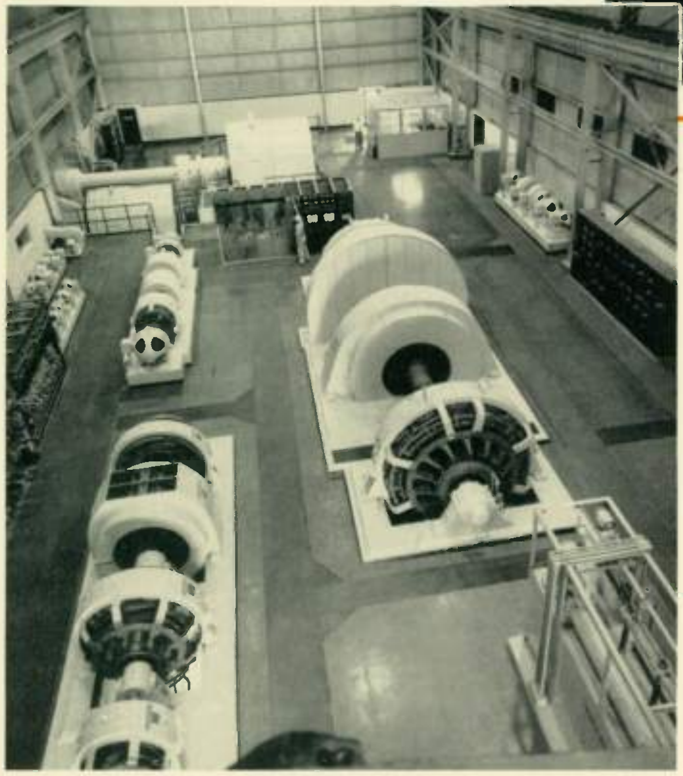


Fig. 6—Transient response of Magamp magnetic-amplifier tandem-mill regulating system with different field strengths on the drive motor. This response for instantaneous insertion of an error voltage is both exceptionally fast and well damped.

Fig. 7—A large slabbing mill with white-hot ingot on the table between the manipulators. The ingot is passed back and forth between the main rolls in the background and is reduced in cross-sectional area during each pass.

Fig. 8—A 7000-hp reversing mill twin drive with 3500-hp, 35/80-rpm main-drive motors (background), and a flywheel m-g set and liquid slip regulator.



reaches proper gauge quickly during acceleration, and that gauge is better maintained at full speed.

This Magamp control system was developed to equal or better the excellent performance obtained from the rotating-regulator systems now in use. It was built and tested on full-scale tandem-mill equipment at the Westinghouse East Pittsburgh Works; a complete system is now being built for a large four-stand mill. The system will use 400-cycle magnetic amplifiers, which have high gain and, compared to that of the generator field, insignificant time delay. High gain assures good steady-state accuracy and fast transient response. Low time delay eliminates any tendency toward overshooting or hunting because the inherently stable single time-delay system is closely approximated.

Response curves and output Magamp voltage curves, shown in Fig. 6, were taken by inserting an instantaneous voltage into the reference bus by suddenly switching a battery into the circuit. This test is more stringent than any possible mill operating condition but serves as an excellent measure of control-system performance. The response, as indicated by the error voltage trace, is less than 0.1 second and is essentially the same at both weak field and full field on the motor. The exciter voltage trace shows that the power Magamp voltage rises to $4\frac{1}{2}$ times normal in less than 1/30 of a second whereas the generator shunt field time constant is approximately four seconds. These tremendous forcing voltages are responsible for the fast system response. This performance is amazing when it is considered that in less than 0.1 second the generator field voltage rises to many times its rated value to force the correction and then returns to normal to prevent overshooting.

Blooming or Slabbing Mill

A view of a slabbing mill with a white-hot ingot on the table is shown in Fig. 7. Such ingots weigh several tons and are approximately 24 by 24 inches in cross section. The cross section is reduced by repeatedly passing it between the main rolls, which must be reversed for each pass. The finished product can be a slab four inches thick by 48 inches wide or a bloom with a 15- by 15-inch cross section.

To position the rolls for each succeeding pass the top roll is moved up and down by the screwdown drive. The tables must also be driven by reversing drives, as must the feed rolls, which are table rolls adjacent to the mill. The heavy manipu-

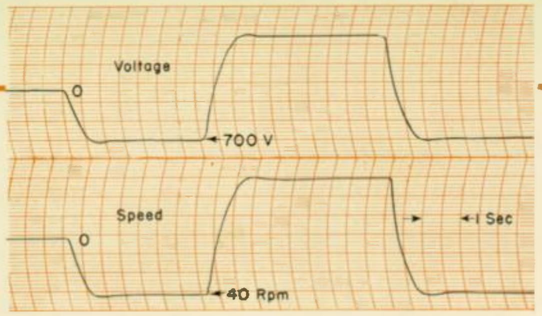


Fig. 10—Reversal of speed and voltage for a 10 000-hp, 40/100-rpm twin-motor drive from base speed to base speed in 1 second.

Fig. 9—Schematic diagram of the regulating system used on reversing mill.

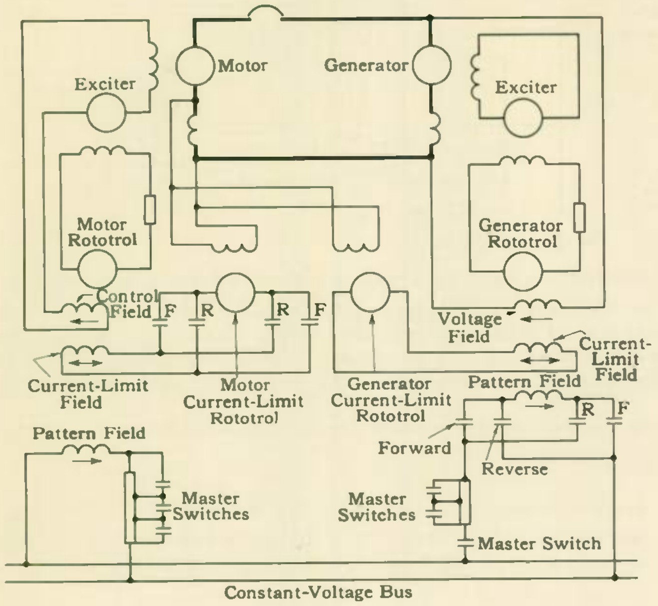
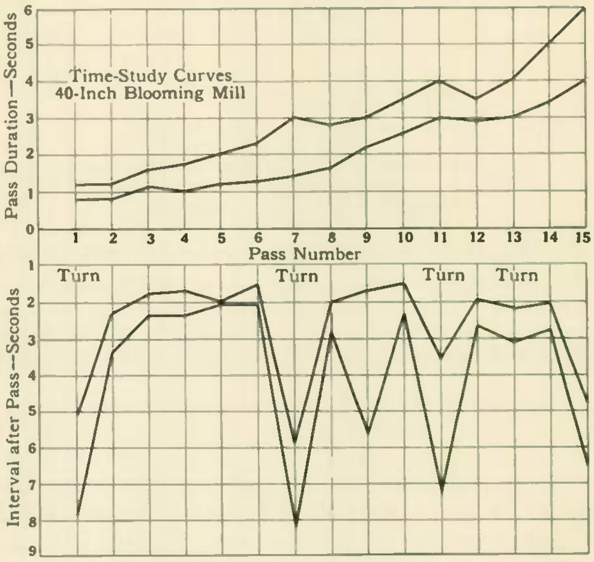


Fig. 11—This shows the maximum and minimum pass duration and intervals after pass for a blooming mill.



lators shown in the foreground are used as guides to position the ingot for passes through various parts of the main roll body. The fingers, which operate from the slots that can be seen in one manipulator, are used to turn the ingot when necessary. Modern practice is to drive such auxiliaries with rotating-regulator-controlled variable-voltage systems.

Main Drive

The twin motors of the main drive of a typical mill, shown in Fig. 8, are each rated 3500 hp, 35/80 rpm. Such motors are designed for an occasional peak torque of 2.75 times rated value and frequently repeated torques of 2.25 times rated value. The flywheel motor-generator set that supplies power to the main drive motors is shown in the foreground, as is the liquid slip regulator for controlling the input to the wound-rotor motor driving the set.

The main circuits for the reversing mill main drive are shown in Fig. 9. Such drives have as many as four generators and as many as four main motor armatures. For example, two 12 000-hp drives are now under construction with double-armature, twin-drive arrangement for the main rolls utilizing four 3000-hp motors. These motors are supplied with power from four 2500-kw d-c generators. The mills also have edging rolls, driven by a 4000-hp double-armature motor supplied with power from two 1750-kw generators.

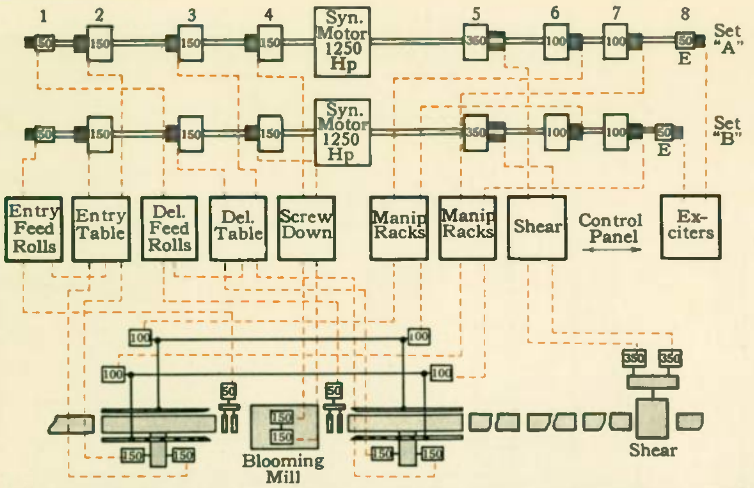
Rototrol rotating regulators are used to regulate the motor field current, the generator voltage, and to assure proper division of load where generator or motor armatures are operated in parallel. The exciters and Rototrol regulators are provided with ceiling voltages of several times normal in order to force the sluggish fields of the main machines to respond quickly. Current-limit Rototrol regulators are arranged so that if the main armature current exceeds a certain value further changes in motor field or generator voltage will be halted.

Regulator systems for this application should have moderate steady-state accuracy, and good transient response and stability. The response of the fastest reversing mill in the world—a 10 000-hp, 40/80-rpm twin-drive recently installed—is shown in Fig. 10. The generator voltage and motor speed are changed from forward to reverse in one second. A maximum exciter voltage of approximately 10 times normal is necessary to force this very fast response. Most mills have base-to-base speed-reversal times of from 1½ to 2½ seconds.

Auxiliary Drives

The curves of Fig. 11 show maximum and minimum pass duration and intervals after pass in seconds for a 40-inch blooming mill. Integration of such curves over the complete schedule show that the metal is in the main rolls only 30 to 45 percent of the time. The remainder is spent in auxiliary operations, such as changing the screwdown setting, manipulating and turning the ingot, and in bringing the ingot back to the mill on the tables and feed rolls. Such studies indicate that the auxiliaries are much more important than the main drive as regards time, and that usually the tonnage output of the mill is more dependent on the auxiliaries than on the main drive.

A typical layout of variable-voltage auxiliaries for a large blooming mill is shown in Fig. 12. The screwdowns are driven by two 150-hp d-c mill motors; the front and back tables are each driven by two 150-hp mill motors; the manipulators for the right and left sides of the mill are each driven by two 100-hp mill motors; and the feed rolls on each side of the mill are driven by a 50-hp mill motor. The bloom shear, while separate from the mill, also forms a part of the variable-voltage auxiliary layout and is driven by two 350-hp special mill-type motors. The generators for supplying power to these d-c



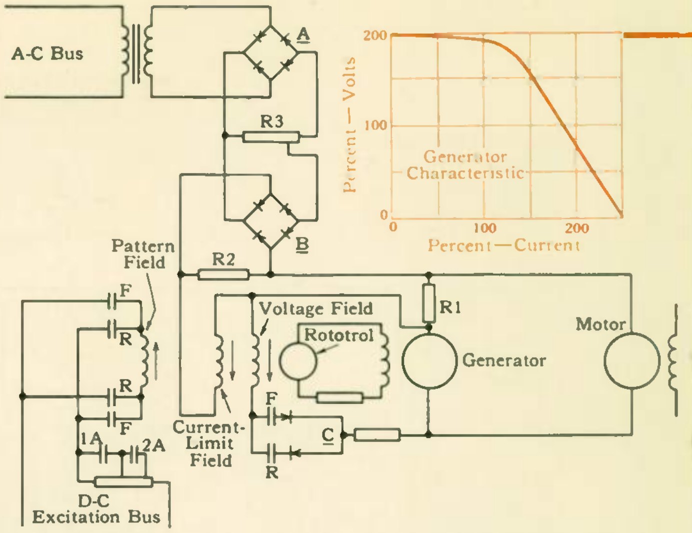


Fig. 12—(Left) Arrangement of reversing mill variable-voltage auxiliaries. Each generator is controlled by a Rototrol regulator.

Fig. 13—(Right) Control arrangement and characteristic obtained for variable-voltage reversing-mill auxiliary drive. The rectified voltage from the a-c bus is applied against the drop across the commutating field of the generator and motor. The rectifier block makes the current-limit field effective only when the armature current exceeds a certain value. This effect is modified by a leak resistor, to give each drive sufficient droop for satisfactory parallel operation. This auxiliary drive control system has successfully proved itself in service.

motors are placed on two separate m-g sets. A generator is provided for each motor; in the event of generator failure the two motors for any one function are connected in series and supplied with power from the other generator. Thus the mill can be operated with one of the sets out of service.

A schematic arrangement of the control for an auxiliary drive generator is shown in Fig. 13. A Rototrol rotating regulator is provided for each generator and acts as a voltage regulator with current limit. The generator voltage is measured by the voltage field and compared to the pattern field, which is under direct control from the operator's master switch. The current-limit field modifies the effects of the other two fields so that the characteristic curve shown in Fig. 13 is obtained. This current-limit field is effective only when the armature current exceeds a certain value. Operating results with this scheme have been excellent. Three hundred and thirty-three such units are in service or planned.

A regulating system with moderate values of gain and reasonably fast transient response is necessary for these applications. The best performance is obtained if the regulator system is fast enough always to force current-limit operation. For a recent drive the values of acceleration, deceleration, and reversal time with an average of 200 percent of motor capacity, and taking into consideration friction loads, were estimated as in table I. These values are well within the response time obtainable with the rotating regulator system. This can be determined from the response curves shown in Fig. 14. The top test shows the Rototrol and the generator voltage with the motor disconnected for a start and several reversals. The start is made in less than one-half second and a full reversal is made in less than one second. These times are lower than the values of table I by very comfortable margins. This test was taken by actually moving the master switch. These operations are indicated by the jumps in the Rototrol voltage curve. A somewhat faster time could be obtained by applying the pattern field in one step and eliminating the approximate 0.2 second required to move the master switch.

TABLE I—TIME VALUES OF A RECENT DRIVE

Application	Acceleration Time	Deceleration Time	Reversal Time	Motor Arrangement
Mill Tables	1.4	1.0	2.4	2x200 hp
Manipulators	1.1	0.7	1.8	2x200 hp
Screwdowns	3.0	1.0	4.0	2x200 hp
Feed Rolls	1.4	1.0	2.4	2x17 hp

The lower response curve shows the main generator amperes and voltage on a start and a reversal with the motor connected and driving the mill table. Here the regulating system forces the drive into current limit and a full reversal is made in approximately 2.5 seconds, which agrees closely with the table below. Note that the current limit is effective in holding peak current to 250 percent of rating. Normal operation of the master switch was made in the test so that the results are equivalent to operating conditions. Here again, note the high momentary voltage required across the main generator field in order to force a quick response. The steady-state voltage across the generator field in this instance is approximately 35 volts. The Rototrol regulator reaches a peak of 200 volts on an acceleration and a peak of about 270 volts on a reversal.

Side-Trimming Line

A modern high-speed side-trimming line offers an excellent illustration of the use of several regulating systems. Such lines are used to trim both edges of the strip preparatory to shipment or further processing. Within a few years the top speed has more than doubled, which has increased the drive problem to an unusual extent. The problem on the reels is mainly one of high stored energy. If the speed is doubled the horsepower of drive motor doubles, but the stored energy in the coil of strip increases four times. This alone doubles the accelerating and stopping torques. The present trend toward use of larger coils further increases them. Apart from this, the speed range over which the drive must operate successfully is also doubled. Threading and low-speed operation has remained essentially the same, so that higher top speed materially increases the range. Another problem peculiar to these lines is that of strip guiding. The slower speed lines use a loop on both sides of the trimming knives so that the strip can be easily guided into the knives and into the winding-reel tension bridle. At higher operating speeds the stored energy in the

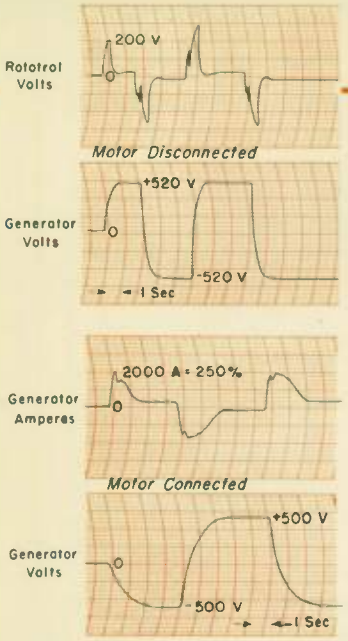


Fig. 14—Transient response of the variable-voltage reversing-mill auxiliary control scheme shown in Fig. 13.

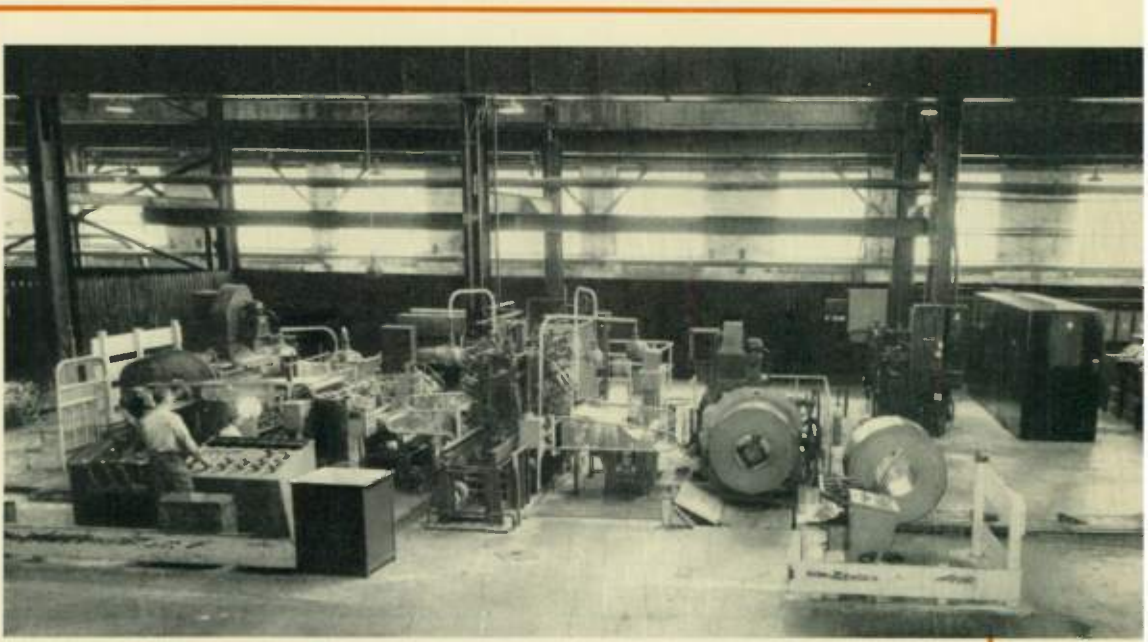


Fig. 15—An overall view of a side-trimming line. This processing line operates consistently at a speed of 3500 rpm.

strip is such that it will not form a satisfactory loop nor guide properly. The line is operated "tight," i.e., without a loop, and a sensitive edge-position regulator provided that shifts the payoff reel to keep the edge in the correct place.

A side-trimming line that operates consistently at 3500 fpm is shown in Fig. 15. A schematic diagram of the pass line and drive equipment for a typical line appears in Fig. 16. The untrimmed coil of strip is placed on the payoff reel mandrel, is welded to the end of the preceding coil, and then passes through the trimmer knives at slow speed to the winding reel. The weld is cut out, the finished coil stripped, the reel rethreaded, and the line brought up to speed.

The main control factors are as follows: (1) The generator is regulated so that low-speed voltages are constant and the generator responds quickly and uniformly to rheostat position; (2) the payoff motor is regulated to keep constant line tension and to compensate for coil diameter; (3) the side-trimmer speed is regulated for best slitting performance and lowest knife wear; (4) the winding reel is regulated to keep line speed constant and to compensate for coil diameter; (5) the edge position of the strip is controlled within narrow limits for uniform slitting and to get straight coil sides on the winding reel.

Regulating equipment for these functions must perform satisfactorily under variable conditions as follows:

Line speed	300 to 3000 fpm
Coil diameter	20 to 66 inches
Coil weight	30 000 lb max
Strip width	16 to 38 inches
Strip thickness	0.005 to 0.030 inch
Range width × range thickness	14.2

To meet these conditions the line drive uses practically all types of regulators—voltage, current, speed, and position.

Generator-Voltage Regulator

The generator voltage is held proportional to rheostat position by a Rototrol rotating regulator, which supplies the entire generator field. The generator voltage is matched against a portion of the exciter voltage through a potentiometer rheostat. Any difference causes current to flow in the Rototrol field, which acts to reduce the difference. The rheostat is mo-

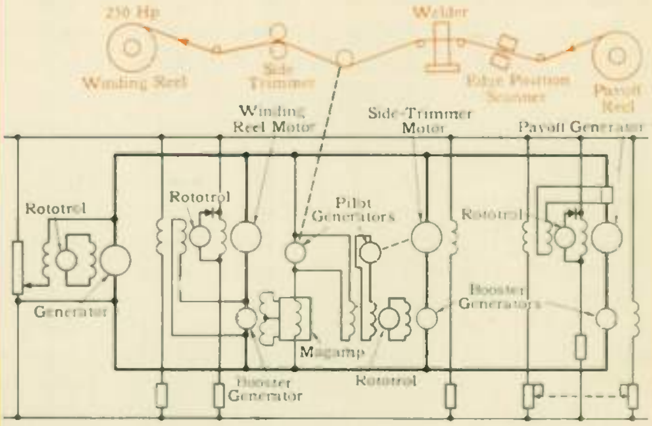


Fig. 16—Schematic diagram of a pass line and adjustable-voltage drive as applied to high-speed side-trimming line.

Fig. 17—Electronic edge-position regulator for a side-trimming line. This is typical of recent electronic regulators.

tor operated and sets the rate of change of speed of the line.

The generator has light running loads as it supplies only the relatively small side-trimmer load and the friction and windage load of the line. However, the stored energy in a high-speed system using large coils is tremendous and the generator must supply this energy during acceleration and absorb it during deceleration. For example, a 66-inch diameter, 30 000-pound coil at 3000-fpm surface speed has stored energy of 1070 hp-seconds, which is equivalent to the energy in a 4000-pound automobile traveling at 67 miles per hour. To put this energy into the coil in a 10-second acceleration requires an accelerating force equivalent to 214 hp at 3000 fpm. Thus, selection of generator rating is purely a matter of the acceleration and stopping times required.

If the strip breaks or the trimmed edge fouls the line, an emergency stop must be made as quickly as possible to prevent waste and to lower the down time for clean-up. A good voltage regulator is essential in obtaining minimum stopping time. It forces a uniform rate of change of generator voltage so that the peak drive-motor armature currents are maintained over a longer time. Thus a much quicker stop can be made with the same peak current. Also the more uniform rate of change of voltage means that the machines can be safely worked nearer their commutating abilities, which further reduces the time required for stopping.

Payoff Tension Regulator

The tension in the strip is set by the payoff reel. A Rototrol rotating regulator modifies the payoff drag generator excitation so that constant tension and coil-diameter compensation are both obtained. Two control fields are used; one to measure line current and one across the exciter bus that acts as a tension reference. These fields give ampere turns in opposite directions so that the armature current is held constant as adjusted by the tension rheostat. As the coil diameter decreases the payoff reel speeds up and causes more current to flow. This disturbs the balance between the two fields and changes the Rototrol voltage to weaken the payoff generator field and reduce the current to the preset value. This action changes the drag generator field as the coil diameter changes, which also changes the drag torque in proportion to coil diameter. Thus constant tension as well as coil-diameter compensation is obtained by use of a simple current regulator. For good operation at low line speed the booster generator voltage is changed in proportion to the tension setting.

Side-Trimmer Speed Regulator

For satisfactory trimming and good knife life it is desirable to operate the trimmer at about 10 percent above strip speed. A Rototrol rotating regulator is used to keep the speed differential constant. A pilot generator driven from the strip measures the line speed and supplies one of the Rototrol fields. The other field is supplied from a pilot generator, which measures the side-trimmer speed. These are adjusted so that the ampere turns of the fields balance when the side trimmer is at the correct percentage above line speed. The Rototrol adjusts the motor speed by booster-voltage adjustment.

Winding-Reel Speed Regulator

Reel drives are regulated for constant tension when another section, such as a mill stand or pair of pinch rolls, sets the line speed. When such devices are not available, the winding reel motor must be regulated to hold the strip speed constant as the coil builds up. A Magamp magnetic-amplifier regulator controls motor speed in proportion to generator voltage. A pilot generator driven from a roll in contact with the strip has its voltage applied directly against the main generator voltage. The difference is applied to the Magamp control winding. The Magamp is a two-stage forward and reverse amplifier so that the booster voltage can be changed in either direction. If the speed is incorrect the pilot-generator voltage does not balance the generator voltage and the Magamp corrects the reel motor speed through changes in booster voltage.

A Rototrol regulator compensates the winding-reel field strength for coil-diameter changes. This is done simply by arranging the Rototrol to hold the booster voltage constant. As the diameter increases, the winding-reel motor rpm is decreased slightly by booster voltage reduction to keep the surface speed constant. As the booster voltage tends to drop, the Rototrol increases the excitation of the winding reel, which in turn lowers the speed and causes the Magamp speed regulator to return the booster voltage to normal.

This system works exceptionally well even at low threading speed. It is a good example of the use of two regulating elements to separate the problem of coil diameter compensation and speed control, as compared to the payoff drive that uses only one regulator to perform both functions. When starting from standstill the winding reel must always exert more pull on the strip than the payoff. Otherwise the payoff would win the "tug-of-war" and start the line in the opposite direction. If the speed regulator were in the winding-reel motor field an attempt to increase speed at low voltages would seriously weaken the field and the pull on the strip. With the regulator in control of the booster voltage an attempt to increase speed circulates more armature current so that the pull on the strip is not decreased. Thus the "tug-of-war" is won by the winding reel over the payoff drive.

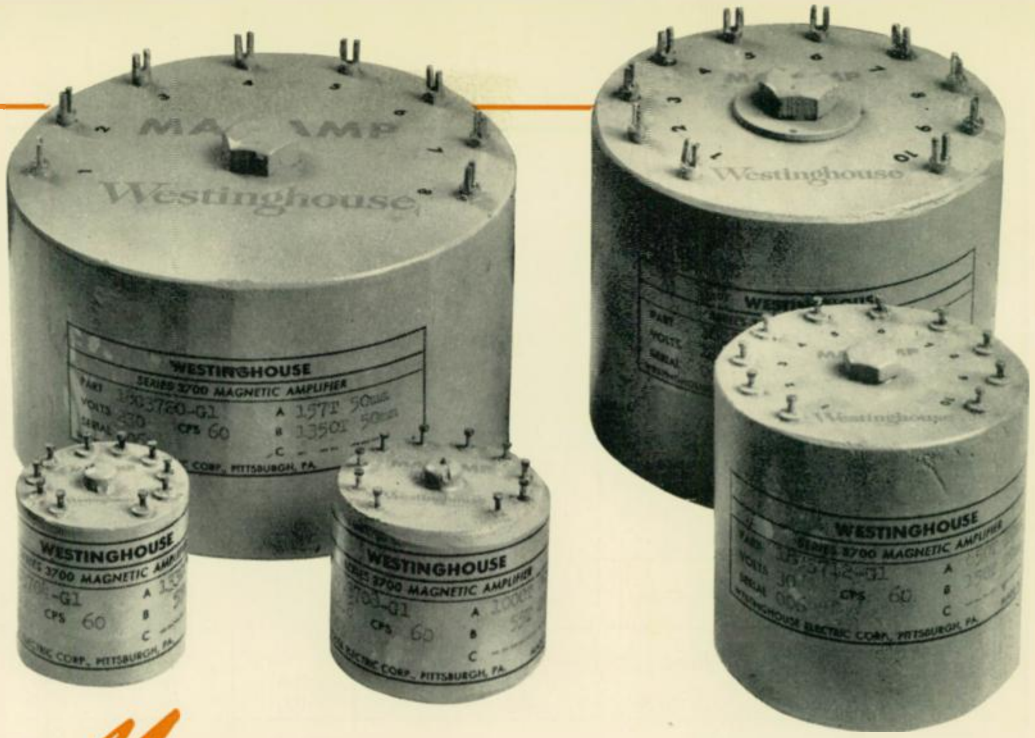
Side-Register Regulator

Slower speed lines of this type have a loop ahead of the trimmer and ahead of the winding reel so that the material can be trimmed and wound straight. On high-speed lines it is difficult to make the loop behave properly because of the stored energy in the strip. These lines are therefore operated "tight" and an edge position is used to guide the strip into the trimmer knives properly and to ensure that a good straight-sided coil is wound. The edge position scanner uses a photoelectric means to determine the strip position. If the strip wanders out of position the photoelectric cell gives a signal to an electronic regulator that controls a small variable-voltage reversing drive. This drives a positive displacement pump, which supplies the hydraulic reel-shift cylinder. The entire reel, its supporting structure, and its drive are shifted back and forth as the edge from the payoff reel changes. Such systems are designed to keep the strip within plus or minus 1/64 inch for rates of runout as high as 60 inches per minute. This is a good example of a regulating device necessitated by higher and higher speeds. The electronic regulator and the small set that supplies power to the hydraulic pump motor are shown in Fig. 17. This construction is typical of present electronic regulators, which are designed for easy accessibility and low maintenance.

The examples discussed are indicative of the wide range of regulating problems that must be solved when applying drives for steel-mill machinery. The industry offers a fascinating array of such problems, many of which are a real challenge to the most ingenious design and application engineers. To see a regulating system control a giant rolling mill smoothly, and yet with authority, provides the inspiration to meet the continuous challenge of higher speeds and more complex systems.

WRH

A device whose largest dimension sometimes is only an inch or two—but whose application possibilities are conversely tremendous—recently bowed into the industrial field. This is the high-performance magnetic amplifier, now finding widespread use in industrial controls. Indicative of its arrival as a practical device is a new standardized series of Magamps, suitable for many control systems.



Standardized *Magamps*

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After its initial introduction, any new device usually pauses to "catch its breath" before plunging headlong into widespread application. During this period it is often tailor-made for specific applications. When the pattern of future applications becomes clearer, one or more standard groups of the device are born. The magnetic amplifier has passed through its breathing spell; a new series of Magamps—called the 3700 series—is suitable for a wide range of communications and industrial applications when properly applied in the overall system equipment. Several of these Magamps are shown in the photograph above.

The Magamps of this series are suitable components for use in amplifier systems for amplifying the minute outputs of thermocouples, photocells, ionization chambers, and strain gauges; they can be applied to arc-welding controls, ignitron-firing controls, automatic battery chargers; and they can be used as components for many amplifier or regulating functions in industrial motor-control systems, such as in steel-mill regulating systems.

The full advantages of Magamps in industrial and communications control systems are not yet being realized. There are several reasons. Perhaps the primary one is the lack of widespread familiarity with the characteristics of Magamps. Another reason has been the difficulty of obtaining flexible general-purpose Magamps for non-critical or experimental applications. These limitations are largely removed with the advent of the new group of Magamps.

Application of 3700-Series Magamps

An engineer considering a particular application usually can reduce his problem to the point where an amplifier is required to drive a particular load from a particular control source. The amplifier must have a power-output level sufficient to supply the load; and control or input windings must be designed to match the signal source. To obtain *optimum* design, a certain amount of calculation and usually some experimentation is required. However, optimum design is unnecessary for many applications. Thus a series of amplifiers with standardized output levels, but with control windings left to the specification of the user, can be directly applied to most non-critical applications. Such are the characteristics of the new Magamp series.

Since most types of magnetic amplifiers, and in particular the high-performance self-saturating types, are sensitive to control ampere-turns rather than the absolute number of control turns, the operating characteristics are expressed in a form independent of the control-winding design.

The new amplifiers have been created for industrial application. They operate on standard 60-cycle supply voltages, such as 6.3, 12.6, 30, 115, and 230 volts. The range of power output levels covered by the new series is 0.04 to 400 watts.

All of the new Magamps are designed to operate in the self-saturating circuit shown in Fig 2. The self-saturating circuit offers high power amplification with relatively short response time. The ratio of power amplification to response time, called the figure of merit, is from 200 to over 3000 per cycle; this compares to a figure of merit of about 4 for a non-self-saturat-

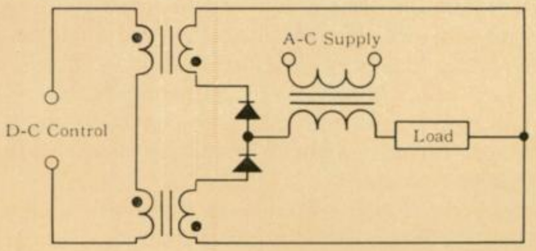


Fig. 2—All the new Magamps of this series are designed for operation in this single-phase doubler circuit.

TABLE I—OPERATING CHARACTERISTICS OF 3700 MAGNETIC AMPLIFIERS

Amplifier Type Number	3700	3704	3708	3712	3716	3720	3721
Type of Circuit	Doubler	Doubler	Doubler	Doubler	Doubler	Doubler	3 phase Doubler
Nominal Power Output, Watts[1]	70	0.04	0.3	7.0	40	180	440
Nominal Ampere-Turns for Control[2]	5.25	0.35	0.60	2.0	3.3	5.5	3.5
A-C Supply:							
Volts	230	6.3	12.6	30	115	230	230 L-L
Frequency—Cps	60	60	60	60	60	60	60
Phase	1	1	1	1	1	1	3
Max. Usable Incremental Figure of Merit[3]	1150	170	310	410	1000	1200	3300
Max. Incremental Power Amplification (3 Cycle Response)[4]	1400	240	400	450	600	2300 (5-cycle response)	7700 (6 cycle response)
Response Time $T = k_1 \frac{N^2}{R} + k_2$ Cycles[5]							
Constant k_1	4.1×10^{-3}	2.6×10^{-3}	3.7×10^{-3}	6.8×10^{-3}	7.5×10^{-3}	8.5×10^{-3}	3.2×10^{-2}
k_2	1.4	1.5	1.6	1.9	2.4	3	3.8
Output Current[6]:							
Rated Amperes	0.39	0.150	0.24	0.60	0.60	1.1	1.71
Max. Power Output Amperes	0.81	0.016	0.603	0.50	0.96	3.3	5.15
Load Resistance:							
Rated (55 deg C temp rise), Ohms	450			20	130	175	150
Max. Power Output, Ohms	140	200	100	28	60	35	30
Max. Incremental Power Amp., Ohms	450	200	100	40	175	250	90
Rectifiers:							
Self-saturating	23D116KA1B	2-IN38's	1D12HA1	2D18HW1	2D120HW1	3D118HW1	24D18KA1C (3 stacks)
Recommended Complementary	23D48KA1B	4-IN38's	1D41HA1	3D41HA1	3D44HA1	4D48HA1	24D116KA1C (3 stacks)
Weight of Reactor Assembly, Lb	4.75	0.13	0.20	0.85	2.5	7.0	6.4
Size of Assembly:							
Diameter	$4\frac{1}{2}$"	$1\frac{3}{8}$"	$1\frac{5}{8}$"	$2\frac{5}{8}$"	$3\frac{1}{2}$"	$4\frac{1}{2}$"	$4\frac{1}{2}$"
Height	$3\frac{1}{2}$"	$1\frac{1}{2}$"	$1\frac{3}{4}$"	$2\frac{5}{16}$"	3"	3"x2 units	5"x3 units

[1] Maximum power output obtainable within the linear range of the control characteristic curve for rated load.

[2] Control ampere-turns necessary to change the output from cutoff to the nominal power output point.

[3] The ratio of the maximum power amplification to the response time.

[4] Power amplification corresponding to three-cycle response time taken over the linear range of the control characteristic curve for the optimum load resistance.

[5] Response time in cycles of supply frequency.

[6] Rms value if output is a-c; average value if output is d-c.

ing, series-connected reactor circuit. The circuit shown, called a doubler circuit, is the most economical of rectifiers and also offers either an a-c or d-c output. The reactors of this series of amplifiers can be used with other types of self-saturating circuits, such as the bridge or center-tap arrangements, but different rectifier assemblies are required and the operating characteristics will be somewhat different.

Components

The magnetic cores used in this series of Magamps employ Hipernik V (50-percent iron, 50-percent nickel) alloy. Full advantage of the material's properties are realized by utilizing the essentially gapless, wound-strip, toroidal-core construction. This core has a nearly rectangular hysteresis loop and a relatively low core loss. In addition, the toroidal shape results in a smaller mean magnetic path length for a given core window area than would otherwise be obtainable. The toroidal construction also results in a saving of space and weight.

The reactors for the new Magamps are vacuum cast in thermo-setting plastic. This assures a maximum of environmental protection, but at the same time produces a relatively small and lightweight unit that is mechanically durable and easy to mount. The vacuum impregnation also helps to ensure long, trouble-free life.

Specially developed selenium rectifiers are used as self-saturating rectifiers. These rectifiers, designed for Magamp use, allow full utilization of sensitive core material.

For each of the amplifiers of the 3700 series the core size, output windings, space available for control windings, and physical assembly are standardized. The complete operating characteristics and the information necessary for the design of control windings are available for each amplifier. Thus great flexibility is obtained by allowing the user complete specification of the control windings within the limitations of space available and manufacturing techniques.

Critical Applications

The magnetic amplifier offers a high degree of reliability with minimum maintenance. Thus it frequently offers advantages over rotating and electronic amplifiers where such characteristics are of great importance. Applying magnetic amplifiers is not, however, a matter of merely replacing a tube or rotating device with a Magamp. Each application must be carefully planned.

This new series of Magamps is not designed to fit every type of installation. Their high ratios of power gain to response time are desirable in a majority of applications. However, they should not be used where input signal powers of less than a few microwatts are to be amplified, or where long time delays, of several seconds or more, are required. Neither are they suitable for situations where extreme linearity and accuracy are required, such as for meter pre-amplifiers. Special designs are required for these critical applications. The design of special amplifiers or complicated systems can best be accomplished in cooperation with engineers closely associated with the development, manufacture, and application of magnetic amplifiers. The new series of Magamps, however, provides a useful tool for many situations.

WRH

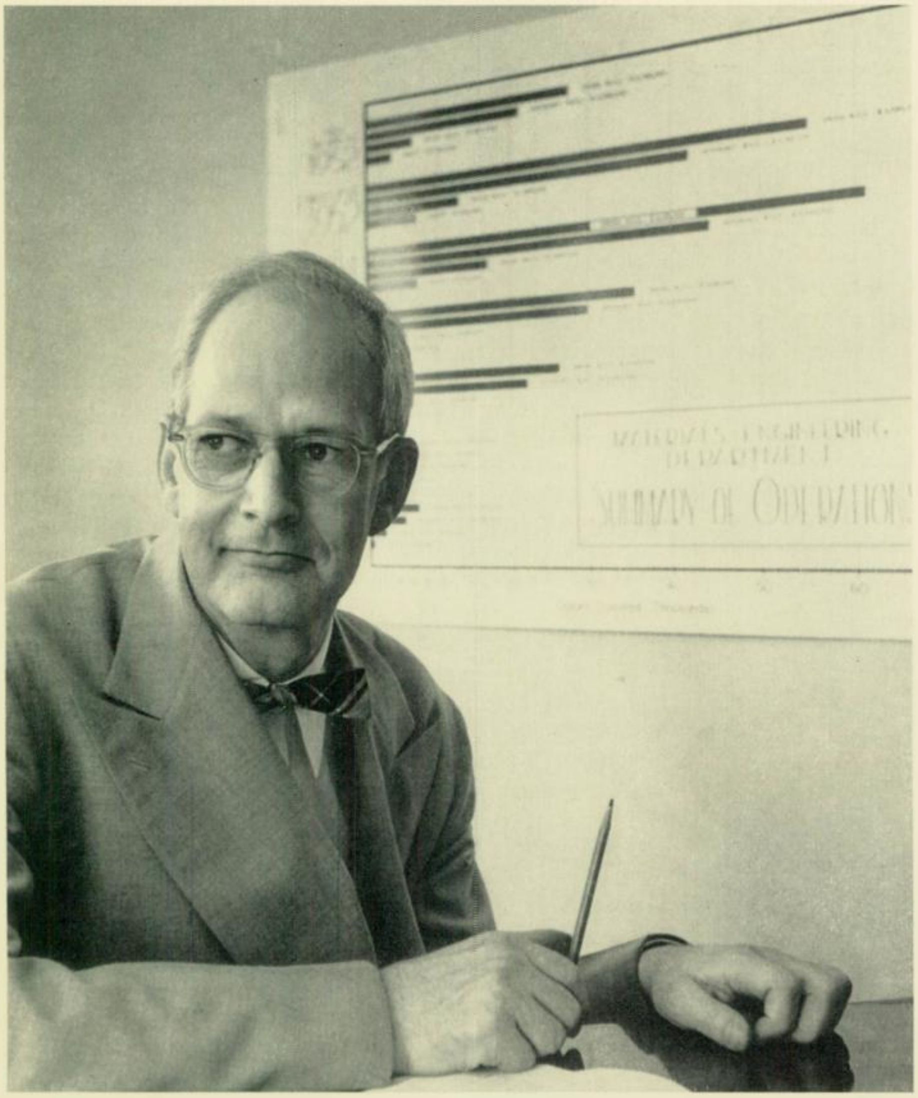
Personalities IN ENGINEERING

Do you sometimes wonder what ever happened to that bright young lad that lived down the street—the one with the insatiable curiosity about how things worked, who was always tinkering with some new gadget, or building some electrical device? Then take a look at John Seastone; his career may well provide some of the answers.

Seastone's particular interest was in things electrical. However, he did not—as the story often goes—sit down at the tender age of ten and decide that he wanted to be an electrical engineer. But he did go at the business of learning something about electricity from a practical standpoint. Blessed with a strong curiosity about things electrical, Seastone studied descriptions of electric motors, then built himself one; he learned of the wondrous Tesla coil, and built one. One by one he accumulated a sizable collection of electrical devices.

By the time he reached high school, Seastone had a better working knowledge of electricity than most people gain in a lifetime. But as his knowledge increased, so did his equipment. Fortunately, a helpful high-school science teacher took an interest in John's work and secured a special room for him in the school to set up and work on his equipment. During this period commercial radio was in its early stages, and there were few sets in Seastone's home town of Madison, Wisconsin. To John this presented another challenge, so he built himself a receiving set. "It was quite an impressive looking piece of apparatus," says Seastone. "In fact, its appearance was considerably better than its reception; but it worked, and I suppose by the standards of radios in those days it was pretty fair equipment."

All this suggests that Seastone probably went on to become a radio engineer, a design engineer, or some kind of electrical engineer. Up to a point, this is true. He did go on to study electrical engineering, and graduated from the University of Wisconsin in 1926 with a B.S. degree. At this point a Westinghouse salesman in Madison, who had watched Seastone's progress with interest for years, lent a helping hand, with the result that John entered the Student Course shortly after graduation. But from here on, his career took one of the many divergent paths on which electrical engineers sometimes find themselves.



Seastone first went to work in the high-voltage laboratory. Then, somewhere—he doesn't remember exactly where or how—he developed an interest in magnetic properties of materials. He spent considerable time doing research on magnetics, a science not nearly as well understood as it is today. He was then in the Materials and Process Engineering Department. This early work was an eye-opener. It brought home to Seastone the tremendous reliance of the electrical industry on materials of all kinds; and it showed him how little was actually known about them. When the whole materials activity was transferred to the Feeder Division, Seastone was made Engineering Manager of the division. In 1945, the need for a Materials Engineering Department as a separate organization to serve all company divisions became apparent, and Seastone became its manager.

Often people who are adept at working with their hands prove far less competent at sitting back and directing the work of others. This is most emphatically not true of Seastone. In fact, one of Seastone's most apparent characteristics is his ability to select or secure the right man for a given job, then give him free rein to do it.

Seastone is a man who gets things done. He typifies that essential man who is at his best in taking a difficult development problem and pushing it through to a successful conclusion. As one of his friends puts it—Seastone likes to take a look at a particular development problem, and, unless the obstacles are completely unreasonable, put forth a major effort to do the job, meeting the problems as they come. He believes that problems must be solved by the concerted effort of many skills and that the advantage of momentum is a necessity. Of course, no small part of the problem is that of choosing the particular material developments on which to concentrate an effort.

In summation, it should be said that Seastone is not the engineer whose name makes technical headlines for producing a world-shaking device or a miraculous new substance. Rather he is analogous to the playmaker on a basketball team; the man who directs the play; who sets up the spectacular shots made by others; and who holds the reins on the team's pace.

A New Set of Equipment for a New Art . . .

Microwave Communication

Microwave signals are relayed at this repeater station, which is a part of a complete system at Baltimore, Md.

On a clear, sunshiny day, line-of-sight signaling was no trick for the Indians—but let a good storm blow up, and the smoke-and-blanket method went with the winds. Present-day technology solves the problem with microwave, and we can now "see" with ease through the roughest weather. Improved 2000-mc equipment handles up to 30 voice channels, or 450 telegraph channels.

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The last five years have seen the amazing growth of a new means of communication—microwave. Federal Communications Commission licenses have been issued for over 600 stations, which furnish approximately 12 000 miles of microwave transmission in various sections of the country.

Because microwave radio can be used so advantageously for certain point-to-point communications services, it is performing many functions that previously have required regular land-wire facilities; and in many instances it is taking the place of the more conventional telephone and carrier wire lines for private communications. Microwave links will control and provide communications for many new pipelines and power lines, which only a few years ago would have necessitated conventional telephone lines or power-line carrier, by which voice and other signals are transmitted at radio frequencies over power-transmission lines.

Even telegraph messages whisk through via microwave between New York, Washington, and Pittsburgh. Several of the inter-city television services, including the coast-to-coast link with more than 100 repeater points, are over microwave channels. Several pipeline systems, some over 1000 miles long, depend solely on microwave systems for their operational communications services.

The microwave communications field is not strictly a new art. It was demonstrated in 1932 that messages could be so transmitted across the English Channel. Actually, however, microwave has had its rise since the war, because the development of high-frequency electronic components for radar made commercial microwave practical.

What and Where Is Microwave?

Microwaves are generally considered to be in the region above 950 megacycles (i.e., shorter than about 30 centimeters or 12 inches in wavelength). Thus, the frequencies are much higher than power-line carrier (100 kilocycles), broadcast (1 mc), short-wave (10 mc), and FM and television frequencies (100 mc). The frequency bands now being used in the United States for microwave communications services are in the general region used for radar and include the 8 mc between 952 and 960 mc, the 140 mc between 1850 and 1990, and the 300 mc between 6575 and 6875 as shown in Fig. 1. These are commonly referred to as the 960-, 2000-, and 6700-mc bands. These and other allocated channels are indicated in the chart on page 203.

By Line-of-Sight Hops

Microwaves have a fundamental difference from the more familiar radio frequencies. Their extremely short wavelength gives them the property of a beam of light—they travel in a line-of-sight path. This characteristic makes them particularly suited to private communications.

The radio energy from the transmitting antenna can, by means of a parabolic reflector, be directed similar to a common flashlight beam. Because the wavelengths are less than a foot long, small reflectors effectively concentrate energy into parallel rays toward the desired location.

By concentrating most of the radiated energy into a single beam, reflectors provide a substantial "gain" in effective transmitted power over a standard half-wave dipole. This gain will be over 300 to 1 for a six-foot diameter reflector at 2000 mc. This means that the "effective radiated power" of three watts into a six-foot parabolic-reflector antenna pointed in the desired direction will be 900 watts or 300 times that of three watts into a simple dipole antenna.

Ionosphere reflection is not effective as at the lower frequencies; these extremely short waves pass on through the ionosphere layer and are not reflected by it. Normal atmospheric refraction causes the lower microwave frequencies to follow to a slight extent the earth curvature, but the range of transmission is substantially limited to a line-of-sight distance between the radiating and the receiving antenna. The line-of-sight is, of course, a function of the surrounding terrain and the antenna tower height. For flat terrain, the line-of-sight distance is usually determined by the practical and economic limit on antenna tower heights—or about 30 miles per hop.

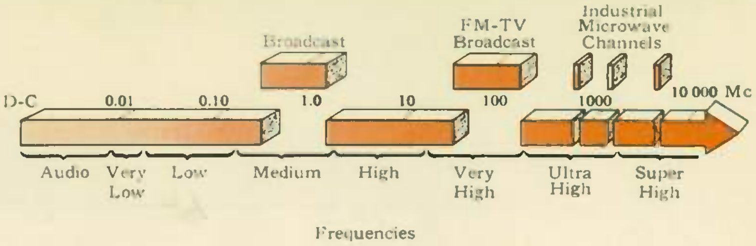

Fig. 1—The three most used industrial microwave channels shown relative to the general regions of broadcast, FM, and television.

These characteristics make microwaves practical for point-to-point service providing private communication channels. They permit the allocation of the same radio frequencies at many other locations, and with proper arrangement even in the same vicinity without interference. Long distances may be covered by the use of repeaters placed in line-of-sight hops across the country.

Much Information on One Channel

An inherent and most beneficial characteristic of microwave radio is its ability to carry a lot of information in a single signal. This is because, at microwave frequencies, it is practical to build equipment that amplifies and transmits a wide band of frequencies simultaneously—and, the wider the band transmitted, the more channels of telephone or telegraph communication that can be carried. To illustrate this point, consider that the normal bandwidth associated with a short-wave communications transmitter operating at 10 mc is about 10 kc maximum. Practical bandwidths for microwave transmitters operating at 2000 mc, however, run between 2000 and 10 000 kc. Thus the microwave channel has from 200 to 1000 times more bandwidth than a 10-mc transmitter. Such wide bandwidth means that a large amount of intelligence can be transmitted over the one microwave signal.

This wide-band transmission capability is exploited through multiplexing, i.e., the use of filters and other equipment by which the signals representing many voice conversations and other types of intelligence can be combined on the microwave carrier for transmission as a single signal, and appropriately separated with little distortion at the receiver points. Several multiplexing techniques are in use that enable a modern microwave transmitter to carry up to 20 or 30 separate voice channels. Each voice channel

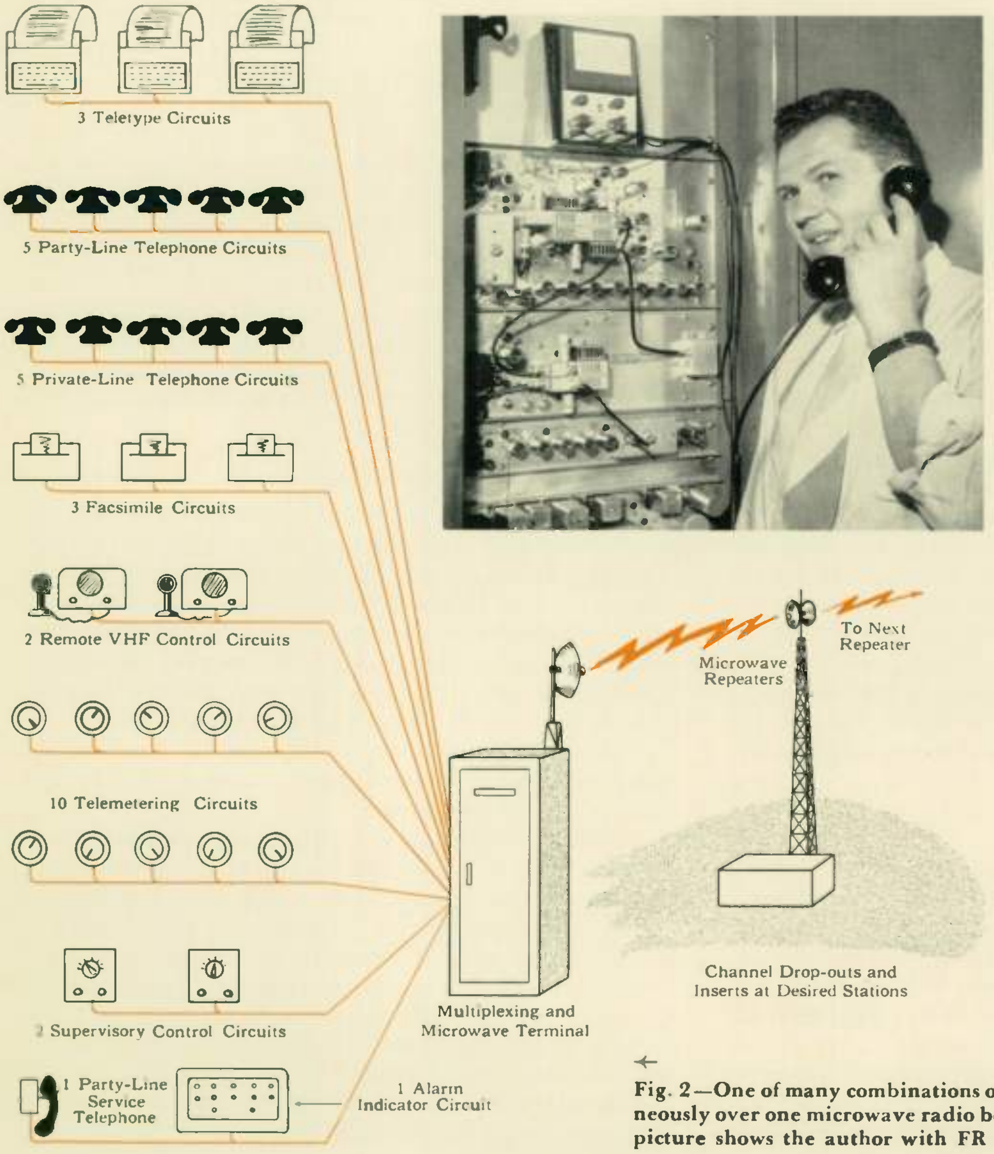

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Fig. 2—One of many combinations of services that can be operated simultaneously over one microwave radio beam in the new 2000-mc equipment. The picture shows the author with FR microwave and FJ multiplexing units.

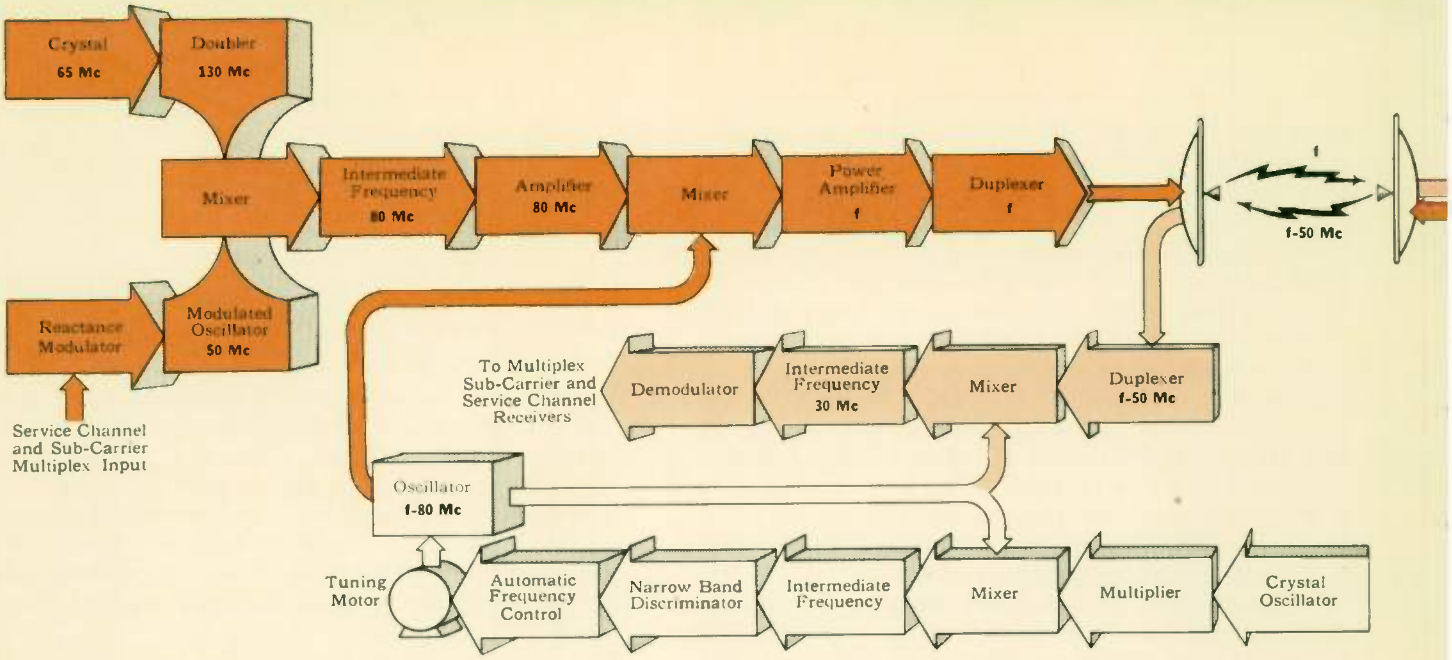


Fig. 3—A microwave system generally consists of combinations of terminal (above) and repeater (right) stations. Since the same local oscillator is used in the repeater to heterodyne the incoming signal down to the intermediate frequency for amplification, and back up to microwave for retransmission, the effect of variations of the local oscillator is eliminated. The 50-mc oscillator is temperature and voltage stabilized so that carrier frequency stability is controlled by the terminal station oscillator.

carries the audio frequencies between 250 and 3000 cycles, a width necessary for acceptable voice quality. Or a microwave link can carry up to 450 telegraph channels, as the band for a telegraph circuit is less than 200 cycles wide.

Low Cost per Channel Mile

This tremendous channel capacity makes microwave installation, operation, and maintenance cost per channel-mile extremely low when distances and amount of intelligence become sizable. The low channel-mile cost is what makes microwave so attractive by comparison with telephone wire lines, and, in many cases, to power-line-carrier type of service.

Where new communication facilities are being installed, there is a certain minimum amount of radio-frequency equipment required for each hop, including transmitter, receiver, power supplies, and antenna facilities. These items are required even for one channel over a distance of one mile. If all applications were this simple, microwave might not compare with standard wire lines. However, when the channels and the mileage increase above an economic crossover point that can be determined for each installation, the microwave begins to pay for itself rapidly as compared with rented lines or new installation of wire lines. Where communications circuits giving satisfactory service already exist, such as power-line carrier or privately owned wire lines, obviously the economics must be studied before any conclusion can be reached. In some instances these more conventional means may be best suited for the purpose.

It Must Be Reliable

One important factor in the economic comparison of microwave and wire lines is the matter of reliability under adverse weather conditions. If communication circuits are primarily intended for operating and maintaining facilities that can be affected by adverse weather conditions, it is obviously invaluable for the communication system to be independent of the weather. The microwave system operating from individual steel towers can be made practically impervious to the ravages of wind and ice which are the source of grief to vulnerable wire lines. Since there is no static interference at microwave frequencies, electrical storms do not hamper communication. Obviously, therefore, a microwave system is of more value in servicing a power-transmission line under conditions of ice and wind than a wire-telephone or power-line carrier.

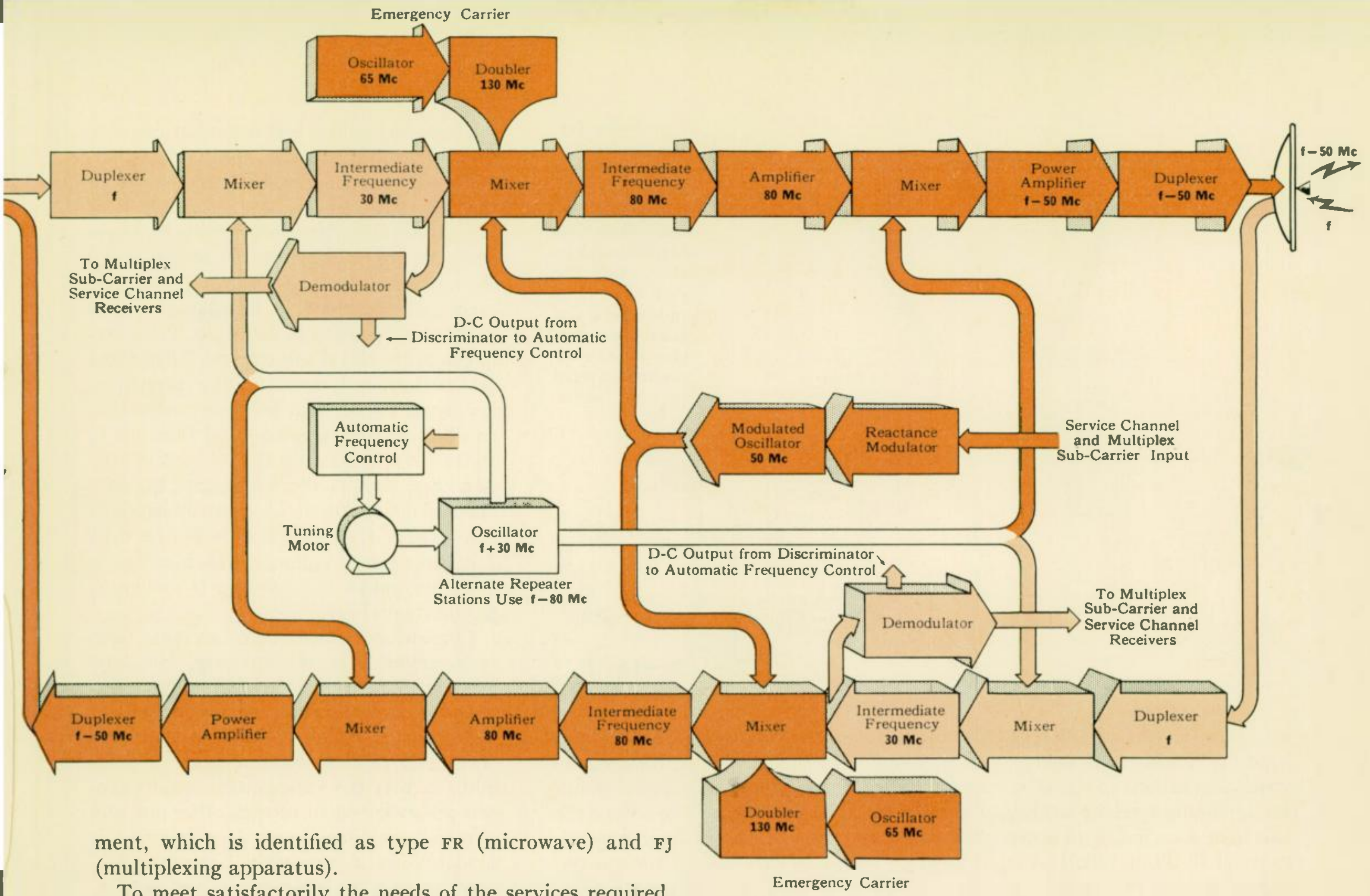
The multi-channel capability of microwave systems makes the equipment of service to a large variety of users. Possible applications include signaling, facsimile, teletypewriter, telemetering, relaying, supervisory control, load control, and extension by remote control of very-high-frequency space radio systems. In fact, a well-designed microwave system can provide any service that direct wires can. This versatility adapts the equipment to many types of users, including extensive applications in electric, gas, and pipeline utilities. The field of application is only barely touched. The next few years will see a tremendous expansion of this type of communication both in this country and abroad.

The New 2000-Mc Microwave Equipment

Westinghouse first entered the microwave communications field in 1948 with equipment operating in the 960-mc band (type FB). This equipment has proved itself in many applications in the field. However, the demand for services to be provided by a microwave channel has grown so rapidly that this equipment cannot always supply the number of multiplex channels that operating companies need. The type FB equipment is limited to 11 channels for typical installations.

Accordingly, new microwave equipment has been developed, based on the latest engineering and field experience, for operation in the 2000-mc band.

A satisfactory microwave system must meet the following criteria. First, of course, the equipment must satisfactorily perform the functions required. Reliability is equally paramount—no communication system is worth consideration unless it is highly reliable. Versatility is likewise important (to both the manufacturer and the operator). It includes both versatility of initial application and of rearrangement and expansion for subsequent needs. Last, but by no means least, is low cost, which includes cost of initial installation, operation, and maintenance. These were the criteria held as guiding principles during the development of the microwave equip-



ment, which is identified as type FR (microwave) and FJ (multiplexing apparatus).

To meet satisfactorily the needs of the services required, the equipment has been made capable of carrying 30 individual, two-way voice-frequency channels (250 to 3000 cycles per second each) which can be used for either voice or telegraph services, or some combination of them. The voice panel is supplied on a 5¼-inch panel complete with self-contained transmitter, receiver, power supply, telephone termination (hybrid), signaling circuit, and is capable of either private or party-line operation. Also available are one-way telegraph transmitters and receivers designed for slow-speed functions (6 cycles per second), high-speed keying or relaying (60 cycles per second), high-fidelity audio modulation (i.e., 6 to 6000 cycles), or further sub-multiplexing for additional telegraph channels operating on audio-frequency assignments. A service channel provides party-line service communication at audio-frequency and signaling facilities. Alarm facilities are available to provide automatic indication and identification of six normal or abnormal conditions of the system. A typical combination of services is illustrated in Fig. 2.

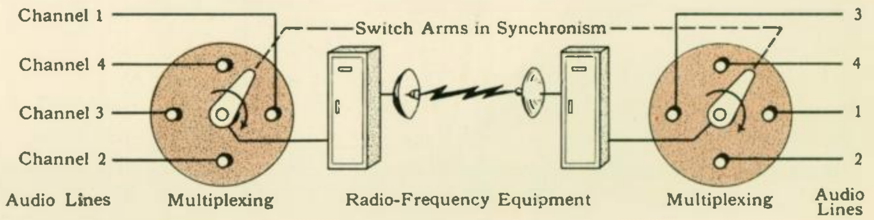
The radio-frequency portion of the equipment is designed to handle the 30 voice channels over 60 hops, each 30 miles long, which can cover a total distance of 1800 miles. This provides a total of 30 voice channels over a distance of 1800 miles or 54 000 voice-channel miles, or a total of 810 000 telegraph-channel miles, since each voice channel, when used for telegraph alone, can be further subdivided into at least 15 telegraph channels.

The extensive coverage is accomplished without prohibitive distortion by the use of a heterodyne-type circuit that performs the repeating functions without demodulation of the radio frequency at each repeater station. This type of circuit has proved highly successful on the microwave system that carries television signals between the East and West Coasts. Triode radio-frequency amplifier tubes give relatively high transmitter output power (3 watts). High receiver sensitivity (13 microvolts), low receiver noise (10 decibels), and low-distortion amplifier circuits are responsible for a high signal-noise ratio even with a large number of channels over a long distance. The microwave transmitter operates with frequency modulation over the government and commercial bands in the 2000-mc region. A block diagram of the equipment is shown in Fig. 3.

The 2000-mc band was chosen over the 960-mc band because of its greater channel-carrying capacity. The selection was made against the 6700-mc band because much greater fading is encountered at the higher frequency. The frequency of the carrier is held very stable (considerably better than FCC requirements) by means of crystal control.

Every effort has been made to attain maximum reliability. Occasionally at microwave frequencies some condition of the atmosphere between stations cause multi-path transmission of signals. This is usually a result of reflection and refraction of the microwave signals by heterogeneous air masses. The signal is broken up into a number of separate signals reaching the receiving antenna by different paths, perhaps of different lengths. This multi-path transmission creates alternate rein-

Fig. 4—A simple mechanical analogy illustrates basic time division multiplexing.



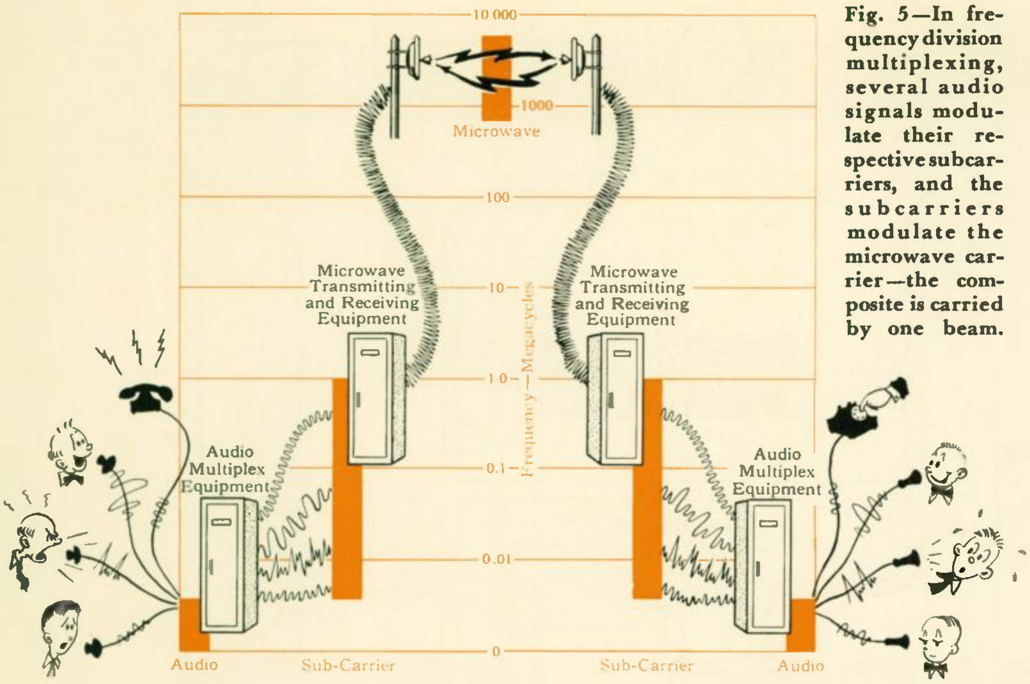


Fig. 5—In frequency division multiplexing, several audio signals modulate their respective subcarriers, and the subcarriers modulate the microwave carrier—the composite is carried by one beam.

forcement and cancellation of the incoming signal as conditions vary slightly, resulting in fairly large fluctuations of input energy to the receiver. If the downward fluctuations in signal strength (fading) were to result in a signal below the minimum receiver sensitivity, service would be interrupted. To reduce the effects of such fading to a negligible point, an excess margin of receiver sensitivity of 30 db or 1000:1 of input power is built into each link of the system.

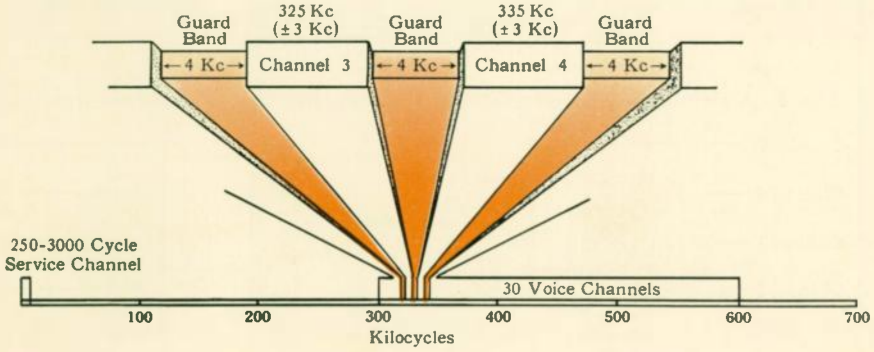
Fortunately, fading on a microwave channel is least when the air is most turbulent, as during storms. This is because the wind makes the heterogeneous air masses homogeneous. Consequently, fading does not occur during severe weather when service communications are most vital.

Multiplexing

One basic factor in any microwave system affecting its reliability is the choice of multiplexing system, which is the method by which a number of voice and other signals are "bundled up" for transmission together on one carrier. Multiplexing can be done in two ways, by time division and by frequency division. These are illustrated graphically in Figs. 4 and 5.

In *time-division multiplexing* the various audio channels are electronically commutated so as to let a sample of each audio signal be sent over the radio transmitter individually but in successive intervals of time. Thus, instead of transmitting all of each incoming signal, the signals are sampled in rapid succession and only the samples placed on the carrier. The received samples of the signal are then commutated in synchronism with the transmitter in such a way that the samples from each channel are directed into their proper line and others excluded. If enough samples of each channel are transmitted per second (approximately three samples per cycle of the highest frequency in the signal or about 9000 cps), then the receiving equipment will obtain the envelope of the sampling pulses, and from that can substantially reproduce the original signal.

Fig. 6—Frequency spectrum showing channel allocation of type FJ equipment.



Frequency-division multiplexing allows all the voice channels to be transmitted over the radio transmitter simultaneously. However, instead of applying all of the many signals directly onto the microwave carrier, each audio channel is translated in frequency and stacked in sequence. These frequencies are called sub-carriers. Then these sub-carriers, each modulated by its particular signal (which can be voice, telegraph, or other intelligence) are used together to modulate continuously the microwave carrier. Specifically, the frequencies between 300 and 600 kc are divided into 30 bands or sub-carriers each 10 kc wide in the type FJ multiplexing system, as shown in Fig. 6. This method of multiplexing is known as frequency division.

Considerable advantage accrues from frequency-division multiplexing. It allows a much more straightforward approach to the problem and utilizes easily understood and adjusted circuits. It has a most important advantage with respect to reliability in that the various sub-carrier channels are independent of each other and any common equipment, such as is required in time-division commutation circuits. The only element the sub-carriers have in common is the microwave channel. The failure of any sub-carrier circuit would not affect the others. In the case of time division, failure of certain elements in the multiplexing system incapacitates the entire microwave system.

Party Lines without "Whistle"

One of the interesting problems of a microwave-communications system is the problem of obtaining party-line operation of a voice channel having a number of parallel terminals located at various stations on the system. In a party line, all sub-carrier sources for that channel must operate on the same frequency to obtain a common talking circuit. If the sub-carrier frequencies were not exactly the same, beat notes or heterodyne "whistles" would be heard at each voice terminal on the party line.

The classical method of preventing this type of interference is to operate party-line sub-carriers "single sideband" which means that the sub-carrier frequency and one of the two intelligence-carrying sideband frequencies are filtered out and only the remaining sideband is put into the microwave radio transmitter. One sideband will not create heterodyne interference when mixed with other similar signals in the radio and sub-carrier receivers. At each sub-carrier receiver, it is then necessary to reinsert a sub-carrier frequency identical to the original in order to recover the intelligence being carried on the one sideband.

This system has been used for many years on telephone carrier circuits that require crowding many channels into the relatively limited frequency handling capabilities of wire lines. The crowding is required to obtain a reasonable number of communication circuits over a single pair of wires.

The single sideband system, however, has certain undesirable characteristics from the user's point of view. The relatively narrow band and sharp cut-off filters needed to separate the sub-carriers from the sidebands results in a comparatively bulky and complex equipment for each channel. A more serious objection is the fact that it is often difficult to maintain the frequency of the reinserted sub-carrier at the receiving end exactly the same as the original sub-carrier frequency that was suppressed at the sending end. If these two frequencies are not identical, it is impossible to use certain types of telemetering or high-fidelity program signals as are used for broadcast work. If the two frequencies drift far enough apart, even regular speech signals become sufficiently translated in frequency range to become unusable.

To overcome these objections, the Westinghouse type FJ multiplexing equipment employs a different method, more suited to the inherent capabilities of a microwave system. To achieve compactness and simplicity, straightforward amplitude modulation is used where the sub-carrier frequency and both sidebands are transmitted over the radio circuit. This is possible even with a large number of sub-carriers because of the greater modulation frequency band handling capability of microwave equipment. The filters are thus much simpler since the system no longer requires complex filters to "squeeze" the sub-carriers together.

Since the sub-carrier frequency is actually transmitted under all conditions of audio-signal input, there is no need for sub-carrier frequency reinsertion at the receivers and therefore the synchronizing problem of single sideband systems does not exist.

Accomplished with "squirt" modulation—To prevent "beats" or heterodyne interference between the several sub-carrier sources on the same frequency for party-line operation, the type FJ multiplexing equipment employs a newly developed technique of "squirt" modulation. This simply means that the sub-carrier frequency source for that channel is normally cut off at all stations where there is no signal going into the microphone. When a voice signal is put into a microphone, the control system immediately provides a sub-carrier frequency source, which is controlled to have an amplitude proportional to the amplitude of the voice signal from the microphone. In this manner, the sub-carrier frequency is always "there when you need it" and in just the correct proportions; yet interfering beats between the various stations on the party line are prevented. This type of "squirt" modulation makes each party station independent of the others and gives superior performance to either manual (push-to-talk) or automatic (voice controlled) "off-on" carrier control systems.

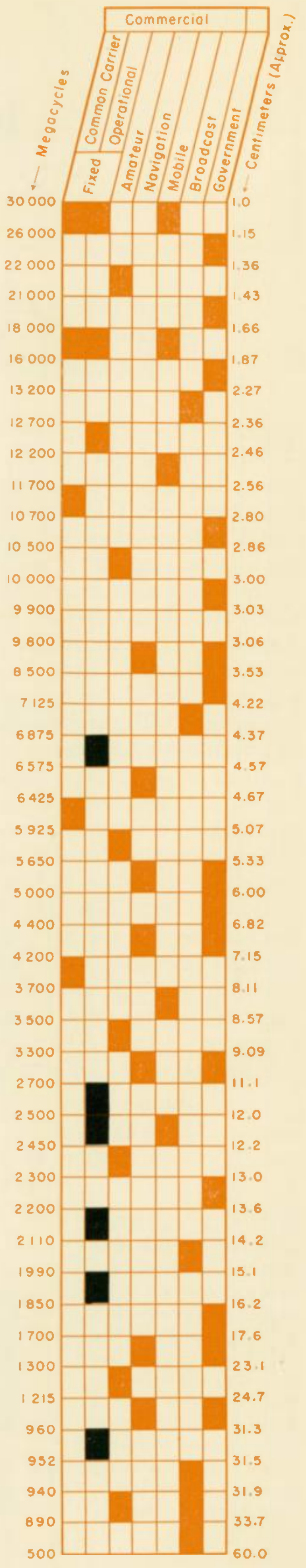
The FJ multiplexing equipment uses the same circuit for either private- or party-line operation except that in the case of private-line operation, the connections are set up to have a constant sub-carrier amplitude in conventional amplitude modulation. The filters on each voice panel can be tuned so as to operate in any of the 30 available sub-carrier channels. This feature permits convenient and inexpensive rearrangement of channel facilities in the field if needed.

Signed, Sealed, and Delivered

In keeping with the trend in the industry, the FR and FJ microwave development program included all the many facets of a complete, and above all, a reliable communications system. The integrated design includes not only the basic radio-frequency and multiplexing equipment, but also automatic standby equipment (to carry on if regular equipment fails), antenna, telephone and telegraph terminal equipment (including, of course, standard telemetering and supervisory control), emergency power supplies, special test equipment, and arrangements for towers, transmission lines, buildings, and fences.

The program further provides a complete retinue of services to be offered in connection with microwave systems including license-application assistance, antenna-site surveys, emergency service and parts, installation supervision, and, if necessary, maintenance contracts. This wide scope of activities is justified because the average industrial user desires a "turnkey" installation, which is an installation provided complete by a single supplier who takes full responsibility, and finally "turns the key" over to the user of the system.

In general, the advantages of microwave systems in many applications give promise of its rapid acceptance among users in industry. The low cost of installation, operation, and maintenance becomes an attractive feature, especially in a time of rising costs. Its reliability under bad weather conditions is a real inducement for many applications. The microwave art has gone through some growing pains in the last few years, but the experience acquired during this period has been put to good use in attaining equipment capable of years of efficient and reliable service.



The spectrum of microwave assignments, with the bands most likely to be used for the present private, point-to-point microwave communications systems are shown by the areas in black.

Magamp Regulation
for Synchronous Machines

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A new look at a long-standing application problem sometimes produces surprising results. A comprehensive review of synchronous-machine excitation methods has resulted in a new Magamp regulating system that has faster response, greater reliability, and requires little or no maintenance.

HEART OF A NEW high-speed regulating system for the excitation of synchronous machines is the magnetic amplifier. The magnetic amplifier (Magamp) has a shorter time delay than a rotating amplifier, and when used in connection with a self-excited exciter, provides a regulating system that has a faster response. A static device, the Magamp replaces the rotating amplifier and eliminates its brushes and commutator, with their attendant maintenance problems. Result—a system that is fast, reliable, and requires little or no maintenance. The basic elements of the system are the same for any type of synchronous machine, so the Magamp regulator can be used with turbine generators, waterwheel generators, or synchronous condensers.

About 50 years ago, a regulator with continuously vibrating contacts was used for automatic control of excitation of synchronous machines. Though satisfactory in performance, it had mechanical limitations. To eliminate them, the rheostatic type of excitation system was developed; an electromechanical contact-making device causes a motor to change the resistance in the main exciter field. This system, more than 20 years old, is still being applied. Although the old vibrating regulator system controlled the field of a self-excited exciter, the contact-making voltmeter system uses a separately excited main exciter, regulator-controlled motor-operated rheostat, and constant-voltage pilot exciter.

Some ten years ago the rotating amplifier was developed into the Rototrol system, using an impedance-type regulator. The system has performed well, but nevertheless the Rototrol requires a commutator. Then, too, the Rototrol system requires careful adjustment. Another system, using an electronic main exciter, has also given excellent results, but is more costly and has the disadvantage of requiring tube replacement.

The Magamp system is an outgrowth of a comprehensive examination of the advantages and shortcomings of these systems. Analog-computer studies were used to analyze complicated circuits involving time constants of various magnitude, and the other variables associated with the operation of synchronous machines. The result of these studies is the regulating system illustrated in Fig. 1.

The synchronous machine has a self-excited main exciter; manual control of excitation is accomplished by adjusting the motor-operated field rheostat. This provides a manual control that is simple and easily understood by the operator.

The main exciter has two separately excited control fields that are energized by the power Magamp. Under regulator control, the motor-operated main exciter field rheostat is set manually to produce a base excitation for the synchronous machine. The power Magamp puts energy into either the boost or buck control field to raise or lower the excitation voltage to the value required to maintain a fixed machine

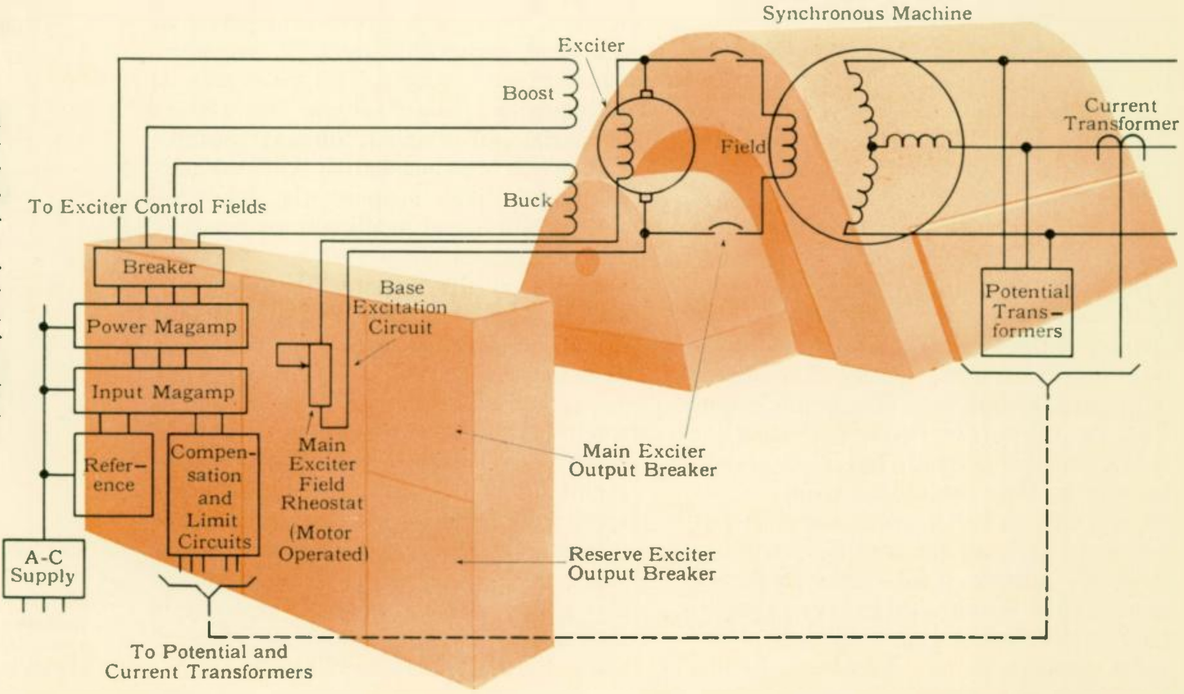


Fig. 1—A simplified schematic of the new regulation system for synchronous machines. Magamps amplify the output of the regulator circuit before it is fed into the main exciter's control fields to raise or lower the machine voltage. The entire regulating system is assembled in switchgear cubicles.

terminal voltage. The combination in the main exciter of a self-excited field and separately excited control fields provides simple and effective control of the exciter voltage. There is a definite advantage over separately excited main exciters, because loss of the separate excitation does not seriously disturb the main unit under normal operating conditions. Operation continues with the excitation provided by the self-excited field, as under manual control. The use of separate fields to provide the buck-boost energy eliminates switching in the self-excited field circuit when changing from manual to automatic voltage control.

The four static components of the Magamp regulating system are shown schematically in Fig. 1. The reference component, energized from a separate a-c supply, develops the reference quantity used as a basis for comparison. At a-c supply frequencies of 70 and 140 percent of normal, the reference error is less than 2 percent. Variations within the usual operating range of ±0.5 percent of the base frequency cause less than ±0.1 percent error. Thus, the reference is ideal for waterwheel generators, which are subject to elevated frequency and voltage following load rejection and during runaway conditions. The increase in synchronous-machine terminal voltage above the reference causes the regulating system to force down the excitation voltage and attempt to maintain approximately the predetermined voltage level even though overspeed has increased the frequency.

The compensation and limit circuits are energized from the synchronous-machine terminal voltage through potential transformers, and from phase current through a current transformer. The compensation circuits provide reactive-droop compensation as required by the system and line-drop compensation. Reactive-droop compensation causes the proper distribution of reactive kilovars among machines that operate directly in parallel. Line-drop compensation causes the regulating system to maintain constant voltage at some point on the system remote from the machine being regulated.

An underexcitation limit is normally provided in the limit circuits for all synchronous machines. It prevents the regulator from reducing the exciter voltage, and consequently the synchronous machine excitation, to a point that would jeopardize the stability of the machine with the system. The lower limit of excitation can be adjusted as kilowatt and reactive load changes. In any case, the lower limit is a variable that depends on machine loading. An overexcitation limit can also be provided for synchronous-condenser applications where the maximum continuous load must be limited.

The synchronous-machine terminal voltage, as modified by the compensation and limit circuits, is supplied to the input Magamp where it is compared with the reference quantity. Any deviation of the terminal voltage from its normal regulated value causes a difference between the reference quantity and the voltage output of the compensation and limit circuits, which becomes an error signal. The error signal is amplified in the input Magamp and supplied to the power Magamp. The power Magamp actually includes two magnetic amplifiers; one biased to respond to a boost error signal and energize the boost control field, and the other biased to respond to a buck signal and energize the buck field.

The a-c supply for the reference unit and magnetic-amplifier circuits is an item of importance. The purpose of the regulating system is to control the terminal voltage of the synchronous machine, which is subject to minor variations due to load changes. During violent disturbances due to power-system faults, the synchronous-machine terminal voltage may be depressed to a low value.

To provide maximum reliability of the regulating system, the a-c supply is obtained from a permanent-magnet generator that is driven by an induction motor. Having no commutator, slip rings, or brushes, the permanent-magnet generator set is a rugged and reliable device that requires no regular inspection or maintenance. A flywheel provides sufficient inertia to carry the set through voltage disturbances on the a-c circuit that supplies the motor. The m-g set can be energized from the synchronous-machine terminals, the powerhouse auxiliary system, or any other acceptable source of power.

One design of reference unit, input Magamp, and compensation and limit circuits is used for all types and sizes of a-c machines. The ratings of the power Magamp and permanent-magnet m-g set depend upon the main exciter size and speed.

The rate of response or time delay of a magnetic amplifier is a function of the frequency of the a-c supply voltage. A higher supply frequency results in faster response and smaller magnetic-amplifier reactors. Therefore, having chosen an m-g set as the most reliable a-c supply, the frequency of the permanent-magnet generator was established at 420 cycles nominally. The result is a regulating system with very fast response and relatively small size. The resultant short-time delays also simplify stabilization of the regulating system.

The components of the Magamp regulating system are assembled in a standard low-voltage metal-enclosed switchgear cubicle adjacent to the exciter field rheostat and field breaker cubicles, as shown in Fig. 1. The entire assembly is completely factory adjusted and tested, and is shipped to the power plant ready for installation. Adjustments and routine checks at the time of installation require little time. The voltage-adjusting unit, regulator cut-out switch, voltmeter, and indicating lamps are items required for control of the regulator and excitation system. These are located conveniently on the operator's control board. The reference unit, compensation and limit circuits, the input and power magnetic amplifiers are located in one cubicle; the main-exciter motor-operated field rheostat is located in the second cubicle; and the main-exciter breaker, and reserve exciter output breakers.

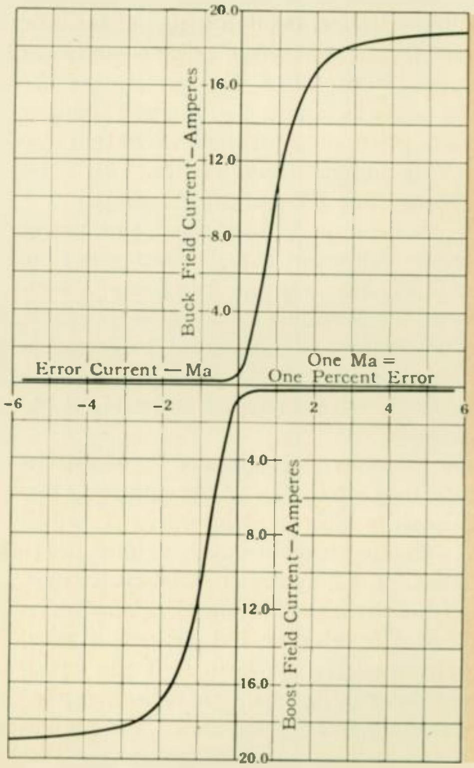


Fig. 2 — Error signal input versus power Magamp current output for both a boost and a buck signal.

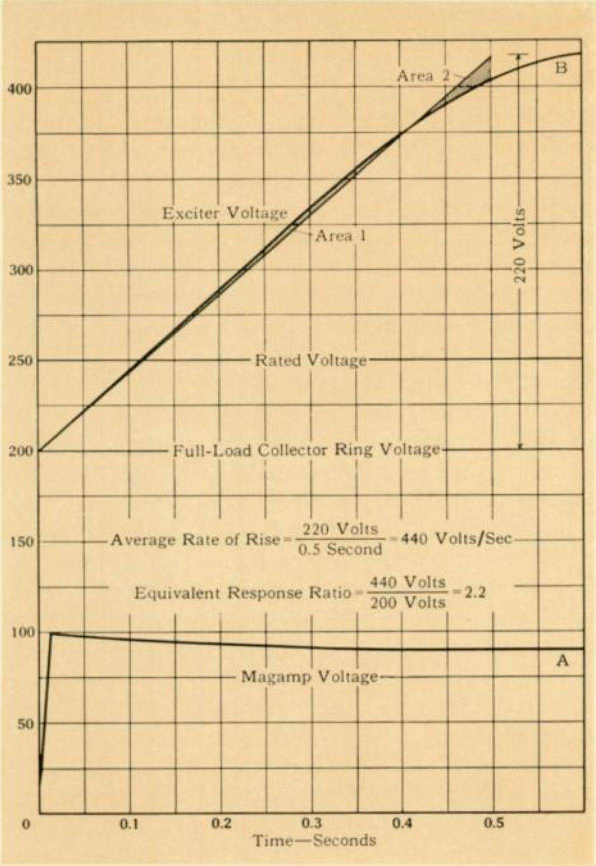


Fig. 3—Rate of response of Magamps and of main exciter. In determining the equivalent response ratio, a straight line is drawn from the origin of the exciter voltage curve so that area 1 equals area 2. The average rate of rise is 220 volts/0.5 second or 440 volts/second. This figure, divided by 200, the full-load collector-ring voltage, from which the rise started, gives an equivalent response ratio for the new excitation system of 2.2.

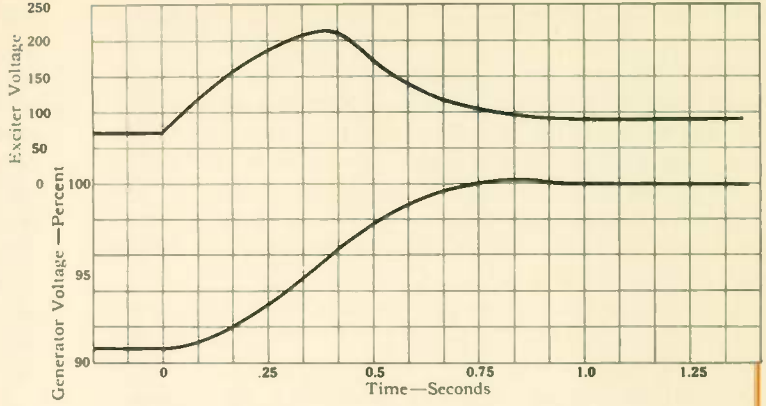
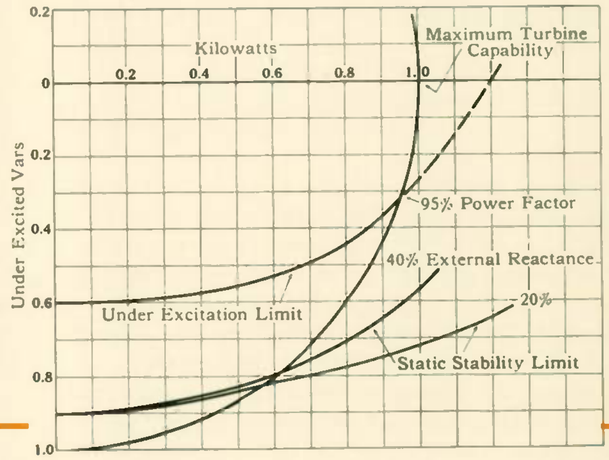


Fig. 4—Response of the regulating system to a suddenly changed setting; generator at no load.

Fig. 5—A typical setting for the underexcitation limit coordinated with the capability curve.



if required, are mounted in the third metal-clad cabinet.

To obtain response and performance data, the 420-cycle Magamp system was tested in conjunction with a 65 000-kw, 81 250-kva, 0.8 power factor, 3600-rpm turbine generator with a direct-connected 215-kw exciter. The results show the Magamp system to be faster in response—for either small or large deviations in voltage—than any known excitation system employing a rotating-amplifier pilot exciter. This is essentially due to the shorter time delay of the Magamp.

The amplification obtained with the input and power Magamps in these tests is shown in Fig. 2, which gives the current output of the power Magamp as a function of the error signal input. The power Magamp is driven to its ceiling output with an error signal of two milliamperes. The deviation in generator voltage required to produce this error signal is approximately two percent, so that maximum forcing is obtained for small deviations.

Test curves showing the rates of response of the Magamps and of the main exciter are given in Fig. 3. The extremely fast response of the Magamps is illustrated by curve *A*, which shows that the power Magamp reaches ceiling voltage in approximately 0.02 second, or 1.2 cycles on a 60-cycle basis. The output voltage of the main exciter, curve *B*, reaches its maximum magnitude of 420 volts, or 168 percent of rated exciter voltage, in approximately 0.6 second. If the equal-area criterion of determining exciter response ratio is applied to this curve, that is, making area 1 equal area 2, the equivalent response ratio of the excitation system is 2.2.

A series of tests was made in which the magnitude of the regulated voltage was suddenly changed a predetermined amount and the recovery rate of the a-c generator voltage recorded. A typical example is given in Fig. 4, which shows the main exciter increasing from 72 volts to a maximum of 212 volts in 0.38 second, while the generator voltage changes 9.2 percent to the new value in 0.72 second. The absence of overshoot illustrates the excellent stability of the system.

An increasingly important requisite for generator voltage regulating systems is the ability of the system to aid in preventing "pull-out" or loss of synchronism of the generator with respect to the a-c system. The underexcitation limit used with modern regulators maintains sufficient generator field current to prevent pull-out under various generator loads. This feature is particularly important with present-day designs of machines when operation is in the underexcited or leading power-factor region. The underexcitation limit of the Magamp regulating system is a new device operating on a new principle and provides a high degree of flexibility in adjustment to meet special requirements. A typical setting for the underexcitation limit for a turbine generator is shown in Fig. 5 where the limit is coordinated with the generator capability curve.

In considering future turbine generators, lower short-circuit ratio than the present-day standards might be applicable in specific cases. Decreasing the short-circuit ratio reduces the physical size of the unit, but results in a generator that is more apt to be unstable under steady-state operating conditions.

The power limit of a synchronous machine with fixed excitation is a fairly well defined quantity. Operation at loadings beyond this limit is possible under control of a close-regulating, fast-response generator excitation system. This is known as operation in the dynamic stability region, a phenomenon that has long been recognized as a possibility. The Magamp regulating system provides an amplification and degree of response not obtainable with any known system using rotating-amplifier pilot exciters. Therefore, the Magamp regulating system provides a greater steady-state power limit for all generators, including those machines that have low short-circuit ratios.

The Magamp excitation regulating system is a progressive step in excitation-system design. The rotating amplifier is replaced with static magnetic amplifiers, producing a system with faster response, greater reliability, and requiring little or no maintenance. The use of a self-excited main exciter with separately excited buck-boost control fields permits a simple method of manual control, and conversion to regulator control requires no switching in the self-excitation circuit. Of particular attraction is the fact that the Magamp regulating system can be applied to any size, speed, or type of a-c synchronous machine; that is, it is equally applicable to the excitation systems for turbine generators, waterwheel generators, and synchronous condensers.

• • •

The Significance of Generator Short-Circuit Ratio

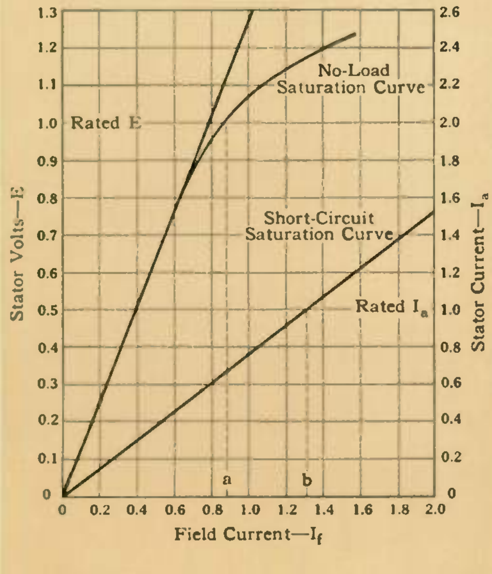
C. M. Laffoon, *Manager, Generator Engineering, Transportation and Generator Div., Westinghouse Electric Corp., East Pittsburgh, Pa.*

THE SHORT-CIRCUIT ratio of an a-c generator is an electrical term often misunderstood. In some degree this is because its definition* is partially arbitrary, and does not give a clear-cut indication as to its significance. Thus an understanding of its importance is more readily achieved by giving less attention to the definition, and considering the ratio as a number—the magnitude of which indicates certain characteristics of the generator, as well as its size and cost.

Most modern central-station steam-turbine-driven generators have short-circuit ratios (SCR) in the range of 1 to 0.8, although the full range of numbers for practical machines possibly extends from 1.1 to 0.5. In large slow-speed machines, such as waterwheel generators and special frequency changers, ratios are higher—up to 2. The SCR of a synchronous condenser may be as low as 0.4. The designers of the machine can calculate these figures with reasonable accuracy, and the results can be checked from test data.

To understand the meaning of short-circuit ratio, consider two machines of identical rating—one with a medium short-

Fig. 1—Typical turbine-generator saturation curves. Short-circuit ratio equals *oa*/*ob*.



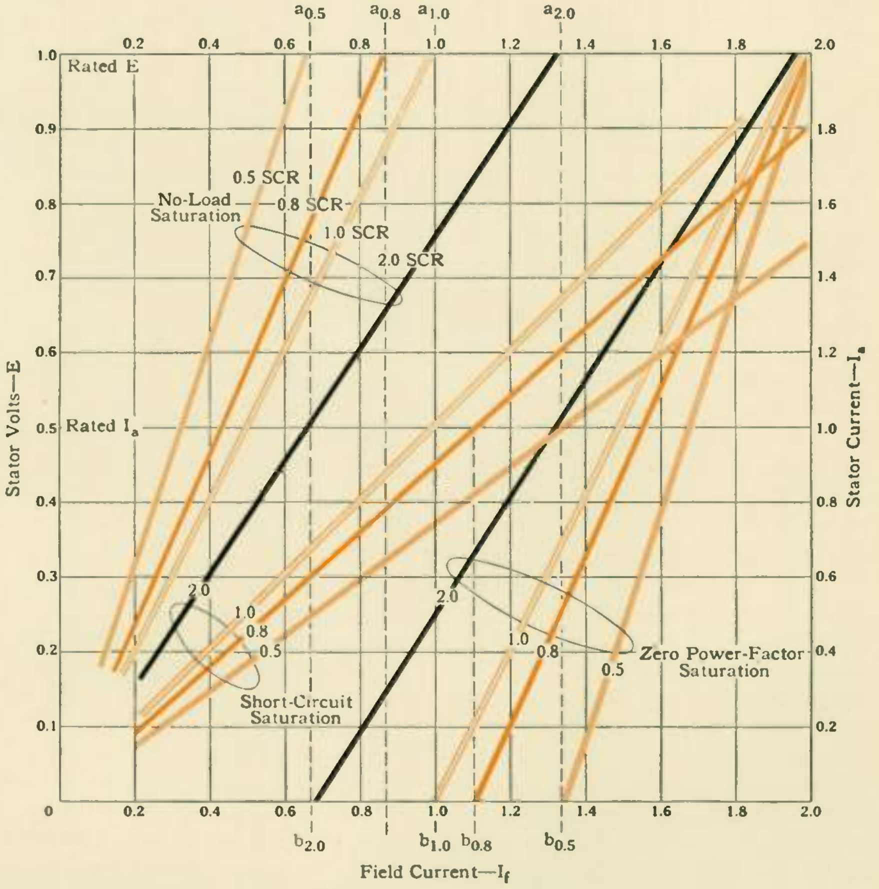


Fig. 2—Turbine-generator saturation curves for different values of short-circuit ratio.

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*Short-circuit ratio is defined as the ratio of the field current required to produce rated voltage at rated speed and no load to the field current required to circulate rated stator current when operating at rated speed under sustained short-circuit conditions.

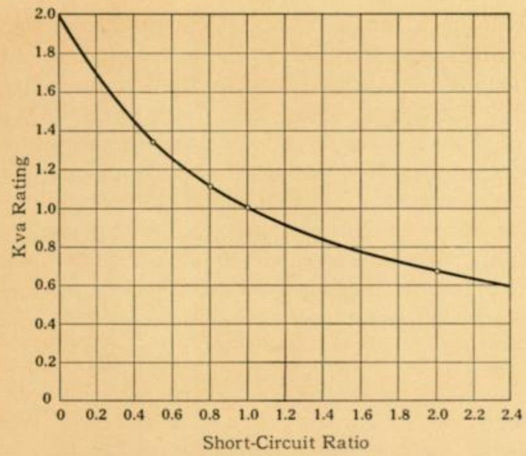

Fig. 3—The relationship of machine rating to short-circuit ratio for turbine generators.

circuit ratio, say 1, and one a low short-circuit ratio, perhaps 0.5. In terms of operation the machines will differ in that for a given change in load, i.e., stator current, the machine with low short-circuit ratio requires a much more rapid and a larger change in field current, i.e., excitation, to accommodate for the new condition. In other words, SCR can be considered a measure of the machine's stability or sensitiveness to change in loading—be it legitimate load change or a fault.

Thus a machine of low short-circuit ratio requires an excitation system that is more reliable, more sensitive, and more able to provide larger changes in field current. The lower SCR machine places far more reliance on its excitation system. Given such an excitation system that is continuously in service, the two generators will do the same job for steady-state load conditions.

The two generators of identical rating but different short-circuit ratio differ physically in that the machine of high SCR contains more materials. The designer achieves the high SCR by adding more copper and iron to active electrical and magnetic parts of the unit. The sizes of the generator housing and structural parts also change, but not in direct proportion to rating or size and cost of the electrically and magnetically active parts; hence the cost of the entire generator changes at a lower rate with respect to changes in SCR.

Briefly, a generator of high short-circuit ratio compares with one of low SCR as follows: (a) it is larger physically, weighs more, and costs more; (b) the initial and sustained short-circuit currents are higher; (c) the ratio of the no-load to the full-load field currents is larger; (d) there is a slight increase in generator losses due to increase in size; and (e) the inherent ability of the unit to maintain voltage and power stability under both slow and fast load changes is improved.

Although there has never been absolute agreement as to the most desirable SCR for a given situation, a rather well-defined practice with respect to turbine generator SCR's has developed. Over nearly a half century there has been a gradual change in the SCR requirements of turbine generators from an upper limit of approximately 1.0 to a lower limit of about 0.8. Coincident with this change, electric-utility systems have grown in size, effective electric interconnection of utility systems in comprehensive regional areas have been accomplished, and more reliable and effective voltage regulating equipment and excitation systems have been developed. Furthermore, rather widespread operating experience has been obtained during recent years for generators built in accordance with present standards. For these the SCR's for the ratings at 0.5, 15 and 30 psig hydrogen pressures are 0.8, 0.69, and 0.64 respectively, simply because the larger the rating of a given machine the lower its SCR. The proposed matching of the generator rating with the turbine rating at 15 psig hydrogen pressure, now under industry consideration, and the SCR of 0.69 that goes with this rating implies general acceptance of this lower SCR.

Since (a) lowering the SCR makes it possible to build smaller and lower cost generators, (b) voltage regulation and excitation equipment have been improved, (c) electric utility systems have become larger and more adaptable for using lower SCR's, and (d) there is a need for less costly generating equipment, a major problem confronts the manufacturer and the user as to how much, and how fast the next reduction in SCR should be. From the standpoint of the generator alone, units with an SCR as low as 0.4 or as high as 0.9 to 1.0 can be built for any rating that the electrical industry will require during the next few years. The use of inner-cooling makes possible the production of single-unit 3600-rpm generators with a 0.9 to 1.0 SCR for ratings up to 300 000 kw.

The operating experience in this country for turbine-generator units having SCR's of 0.5 or less is small. The static and transient stability performance of a generating unit is influenced in great measure by the characteristics of companion units in the same generating station, and in other stations on the system; by the voltage-regulation and excitation systems in use on all units; by the characteristics of the system and its interconnected systems; and by operating practices and procedures. Therefore, the overall problem should be analyzed carefully before making appreciable reductions in generator short-circuit ratio, and any reduction in SCR should be made in "not too large" increments. This program is likely to avoid unanticipated operating troubles due to unforeseen situations and problems.

The operators of several electrical systems in this country believe that turbine generators should have an SCR of 0.8 to 0.9. It is quite possible that as time passes the conditions responsible for this need will change, whereupon generating units with lower SCR may be acceptable. Westinghouse is able to furnish single-unit 3600-rpm turbine generators for any rating and SCR the electric industry will require in the foreseeable future.

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Personality Profiles

R. W. Roberts wasted little time breaking into print with his first story in the Westinghouse **Engineer**. He has been with the Company for about a year. Appropriately enough, his subject is one of the newest of products—a new line of magnetic amplifiers.

Magamps are, in fact, what brought Roberts to Westinghouse. In 1951 he became interested in this novel device and in its possibilities and came to the Magamp Section from Motorola, where he had been a microwave engineer.

Roberts is an Illinois native. He attended public schools in Chicago, and later graduated from Illinois Institute of Technology in 1948. Like so many other engineers, Roberts had a gap in his college course—from 1944 to 1946—occasioned by the war. He stayed on at college for two years after his graduation, concurrently doing graduate work and teaching a number of electrical courses.

* * *

A man setting about to become an expert on motor control might go about it in this fashion—first learn as much as possible about motors, what they will do, what their limitations are; second, spend some time applying motors, especially in tough applications; and third, concentrate on controls themselves. *R. W. Moore*'s experience at Westinghouse has followed just such a course, although he would be the first to disclaim that any planning was involved on his part. Moore graduated from the University of Wisconsin, and after completing the Graduate Student Course, moved into the d-c design section of the Motor Division. After several years of designing motors, he transferred his interests from design to application, joining the Steel Mill Section. With some application experience under his belt, Moore then moved on to Control Engineering. In 1951 he was made manager of the Development Engineering Section of the department, the position he now holds.

C. E. Valentine last appeared here in 1948, when he wrote twice on his favorite subject—regulators. As head of voltage-regulator engineering since 1935, he has had overall responsibility for the development of many types of regulators. Among those fashioned under his watchful eye are the Silverstat, and the Rototrol for excitation control. During World War II various static devices put in an appearance, with the Magamp emerging one of the most promising. Valentine's work, in close cooperation with others interested in the same goal, has contributed to the new Magamp regulation system recently announced. Recently, Valentine was awarded the Westinghouse Order of Merit, the highest honor bestowed by the Company for distinguished service.

* * *

Figuratively speaking, most of our conversations with *J. E. Barkle* seem to take place when he is either just coming in the door from one trip or dashing out on another. The particular reason for this is that Barkle is an engineer in the Electric Utility Section—and that his particular bailiwick is the Pacific Coast district. Thus much of his time is spent working with electric-utility engineers in the eleven western states, Alaska, or Hawaii.

Barkle has been associated with the electric-utility industry since 1939, the year he graduated from Carnegie Institute of Technology. After he completed the Student Course, he went to work in what was then called Central Station Engineering; here he has stayed ever since, except for a stint in the Company's Boston office, where he picked up valuable field experience.

One of Barkle's specialties is excitation systems. He heads the Company's excitation committee, and contributed a new chapter on excitation to the revised Transmission and Distribution Reference Book. Very active in AIEE affairs, he serves on several of its working committees.

* * *

When it comes to thoroughness, the analog computer is tough to match. But there are several indications that *James T. Carleton*, who supervises its operation, comes close. Once, in working on the development of an autopilot, Carleton decided that mere data on man's reactions wasn't enough—so he wired in the man himself. And in his first appearance on these pages he not only turned out one complete technical article, but also co-authored another.

Graduated from the University of Santa Clara in 1942 as one of the poorest spellers in his class (he says), Carleton soon found himself a cryptographic officer in the Army's Signal Corps. Carleton jokingly concedes that this must have been strategy to confuse the enemy. He served with the 7th Army through Africa, Sicily, France, and Germany.

In January, 1946 he was again made a civilian, and promptly entered the Westinghouse Student Course. His eventual assignment was in the electronics section of the Industry Engineering Department.

When the present Analog Computer section was formed in November, 1946, Carleton was selected as one of the nucleus group of three. He has been instrumental in building the Anacom into its present form and in addition has come forth with a major development in the form of an office-type computer. Carleton was recently made supervisor of Anacom activities.

* * *

Nelson B. Tharp—known to many as W3EUN—tries a new medium of communication as he makes his initial appearance in these pages. But there can be little doubt that his true love is radio.

When he was at Northwestern University, he was president of the radio club. He came to the Student Course in 1941 and went promptly to Baltimore and into the design of radar and radio equipment. During his stay in Baltimore, Tharp has been all over the spectrum, from 100 kilocycles—which to Tharp is "practically d-c"—up through the broadcast and shortwave bands to his present location at 2000 megacycles. Since May, 1951 he has been section manager of communication engineering.

Tharp began living, eating, and sleeping microwave last July when he was placed in charge of a design group, isolated from the rest of the design sections, and given the job of developing the equipment of which he writes in this issue.

Tharp's intense interest in radio is also enveloping his entire family, one by one. First, it was his wife's brother, and, when he went away to college, the father-in-law was drawn into the game. About this time, Mrs. Tharp must have realized that the easiest way to talk to Nelson was with a "mike"—so she changed her name to W3MPU. And now, to make the conversion complete, Tharp is busily training his four sons to go on the air.

WRH

Stacker for REFUSE

Although this unusual-looking device looks somewhat like a cross between a huge tractor cab and a rocket platform, its actual purpose is considerably more down-to-earth. But it is still unusual. This is a refuse stacker, which stacks waste from a coal-cleaning plant of the Jones & Laughlin Steel Corporation. Refuse is conveyed up a hill from the cleaning plant by a standard conveyor, powered by a 125-hp motor with speed reducer. It is then dumped onto the stacker (built by the Jeffrey Manufacturing Company), which carries it to the pile. The tractor system, which enables the whole system to be moved at right angles to the conveyor, is powered by 15-hp Life-Line motors through speed reducers. All stacker movements are controlled from the cab.